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Turbine Fuel Alternatives (Near Term)

Augusto M. Ferrara

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16. Abstract

This report discusses the results of a study which investigated several alternatives for turbine fuels, which are being considered for use in the near term, with the intent of identifying the necessary certification criteria. The fuels investigated include Jet-A/ethanol blends, Jet-A/methanol blends, JP-4/ethanol blends, and neat ethanol. The tests were conducted using a T-63 turboshaft engine, which was mounted on the Technical Center's dynamometer. The use of dual fuel systems was also considered.

A short series of flight tests was conducted with a T-34, Mentor aircraft. These tests were used to identify the operating conditions which might result in elevated fuel temperatures.

17. Key Words

Turbine Fuels
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EXECUTIVE SUMMARY

The Federal Aviation Administration (FAA) Technical Center evaluated the use of alcohols as extenders for existing turbine fuels which are used in aviation applications. This testing was conducted on the Technical Center's dynamometer, using a T-63 turboshaft engine.

The testing identified the conditions which are most likely to result in power loss due to vapor formation. These are an ethanol concentration of 12.5 percent, a tank fuel temperature of 52 °C (125 °F), and an engine acceleration from ground idle to takeoff power. The probability of experiencing problems due to vapor formation increased if the base fuel is JP-4 as opposed to Jet-A.

The use of a dual fuel system was demonstrated. The dual fuel system will alleviate some of the phase separation problems which are anticipated with Jet-A/alcohol blends. Both hot and cold fuel were evaluated with this system, and no phase separation problems were noted with ethanol. Apparent solubility problems with methanol resulted in an inoperative fuel flow indicator. The threat of vapor formation was reduced with the dual fuel system. Hot methanol resulted in more vapor formation than hot ethanol.

There was an apparent material compatibility problem which affected the operation of the fuel control unit. This problem was aggravated by the high operating temperatures associated with the hot fuel testing.

The brake specific fuel consumption increased when operating on a fuel which contained alcohol. This increase reflected the reduced energy content of the alcohol used to prepare the blend. There was some evidence that the use of the alcohol blends affected the combustion properties of the fuel.

A temperature survey was conducted with a T-34C Mentor aircraft to determine the operating mode most likely to result in high operating temperatures. The highest temperatures were recorded during touch-and-go operations. A hot soak prior to the touch-and-go sequence increased the operating temperatures.

INTRODUCTION

Aviation kerosenes have been the principal fuels used in turbine equipped aircraft for approximately 30 years. These fuels are petroleum distillates and, as a consequence, they represent a finite resource. Since the oil embargoes of the 1970's, substituting renewable resources for nonrenewable ones has attracted a significant amount of attention. Alcohols have been used as extenders for gasoline in this country, and recently the Federal Aviation Administration (FAA) has been approached to allow the use of ethanol as an extender for Jet-A.

PURPOSE.

The intent of this test program is to provide the data needed to establish meaningful certification criteria for an aircraft designed to operate on one of the following fuels: Jet-A/ethanol blends, Jet-A/methanol blends, JP-4/ethanol blends, and neat ethanol. Special consideration is given to establishing the appropriate criteria for the certification of hot fuels. Potential operational problems are documented, though no attempt was made to highlight operational considerations.

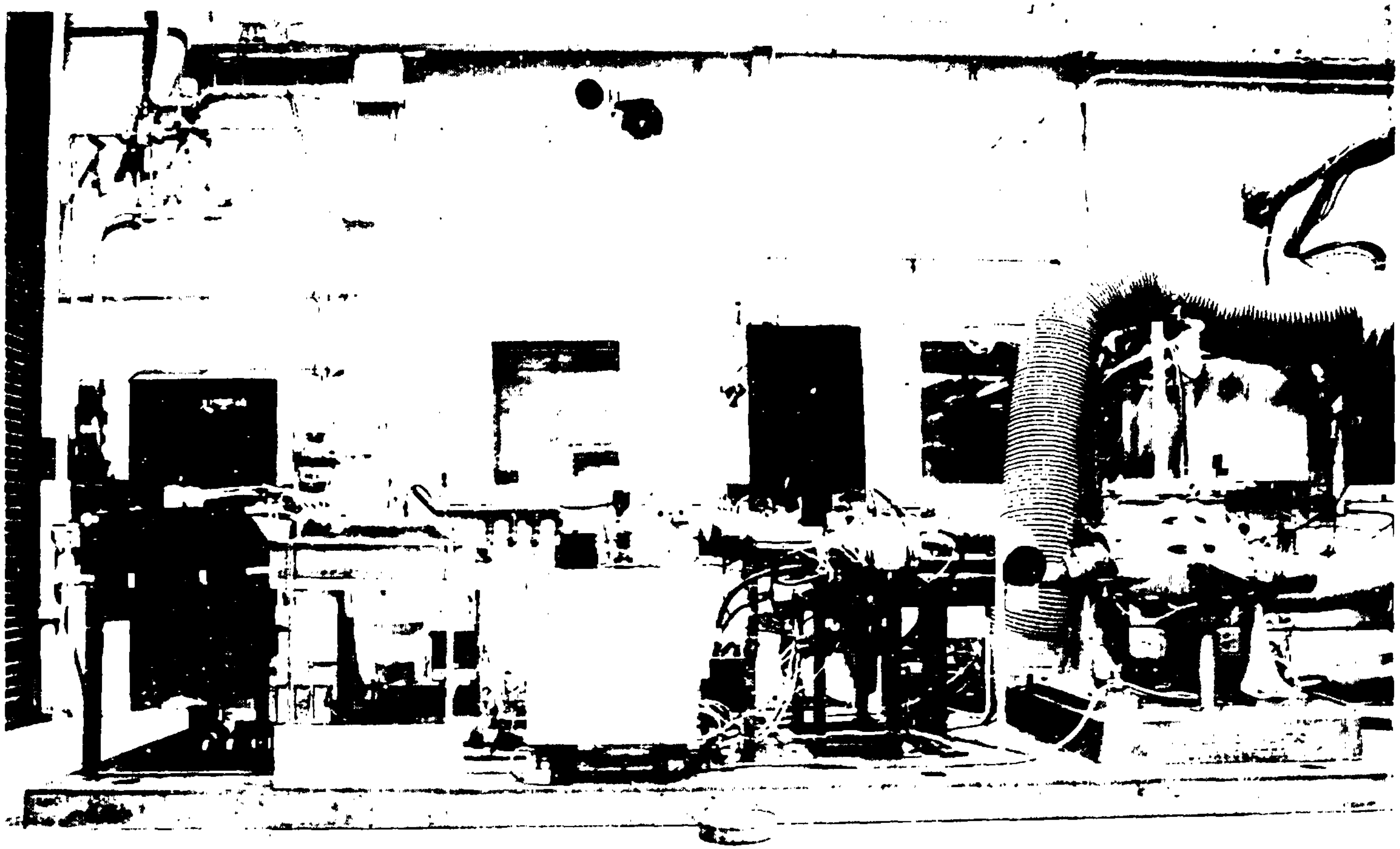
TEST APPARATUS

The tests were conducted at the Federal Aviation Administration (FAA) Technical Center, Atlantic City International Airport, New Jersey. The engine tests were conducted using a T-63 turboshaft engine which was loaned to the FAA by the United States Army. The lab test results reported were obtained using the apparatus and procedures outlined by the American Society for Testing and Materials (ASTM). Below is a brief description of the dynamometer installation used in this test program.

DYNAMOMETER INSTALLATION.

The Technical Center's dynamometer is an eddy current design with an absorption capacity of 373 kilowatts (kW) (500 horsepower) and a maximum speed of 5,000 revolutions per minute (rpm). The T-63 turboshaft engine was coupled to the dynamometer, and a fuselage mounted aircraft auxiliary tank was installed to provide test fuel to the engine (figure 1). To expedite the installation, a reduction gearbox was not used. As a consequence, the maximum speed of the output shaft was limited by the dynamometer requirements. This meant the engine would operate at less than its design speed, which in turn reduced the power developed. The Technical Center considered this acceptable since baseline data were to be established using Jet-A.

The test fuel tank was modified by installing heat exchangers along the bottom of the tank. A hot ethylene glycol/water mixture passed through the heat exchangers when heating the test fuel. An electronic controller maintained the target temperature as required for the test in progress.



Legend:

1. Main Fuel Tank
2. Alcohol Tank
   (duel fuel system)
3. Instrumentation Box
4. *T-63 Turboshaft engine*
5. Dynamometer absorber

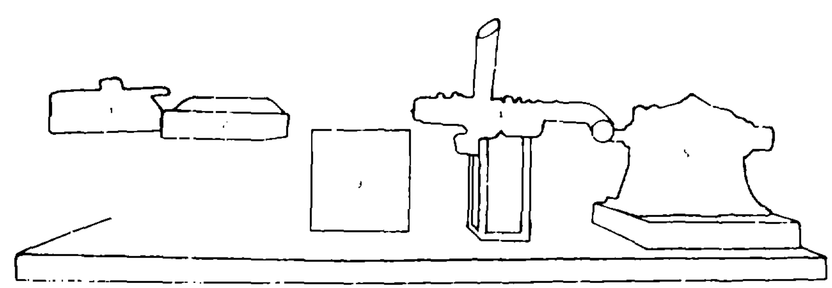


FIGURE 1. DYNAMOMETER INSTALLATION

Electrical heating tape was wrapped around the fuel line and the temperature of the outside wall of the fuel line was regulated using an electronic controller. The fuel tank was insulated as were the fuel lines. Under normal operations, the test fuel would be drawn through the check valve (figure 2). If the boost pump was activated, the check valve would close and the boost pump would supply the engine. If the valve to the building supply was opened, the pressure from the building supply would seat both check valves, and Jet-A from the building tanks would be supplied to the engine.

At the conclusion of testing with the turbine fuel/alcohol blends, a second fuel tank was installed. This tank allowed testing in a dual fuel system configuration (i.e., two tanks feeding different fuels to the test engine). The larger tank contained Jet-A and the smaller tank contained alcohol. As before, the ethanol tank and associated fuel lines were heated, with the temperature of each component independently controlled. A spring loaded check valve was installed in the ethanol supply line (figure 2). Unde- idle conditions, there would be insufficient pressure to open this check valv 's allowed for idling and shutdown on neat Jet-A without any input from th' . Whenever the boost pump or the building supply was selected, this .a .ld seat and stop the flow of alcohol.

The gas generator lever was operated remotely using a pneumatic actuator. This actuator was adjusted so that full travel was accomplished in 1.5 seconds. This allowed the operator to select takeoff power from the idle setting by throwing a switch, without exceeding the recommended rate of change for the power lever.

Data were recorded using an automatic data acquisition system, which recorded all of the parameters listed in table 1 at a scan rate ranging from 0.5 to 15 seconds.

FUEL PREPARATION.

The turbine fuel/ethanol blends were prepared in a 208-liter (55 gallon) barrel which was equipped with an electrical heater. This allowed for heating the base fuel (either Jet-A or JP-4) to a minimum of 20 °C (68 °F) prior to mixing. This temperature was selected based on the results of a phase separation survey conducted by the Technical Center (reference 1). Following mixing, the test fuel would be transferred to the test tank using a hand operated wobble pump.

T-34 MENTOR AIRCRAFT.

A T-34C Mentor aircraft, which is on loan to the Technical Center by the United States Navy, was instrumented to obtain an overview of the cowling temperatures in the vicinity of the fuel system components during different flight conditions. This aircraft is a single engine trainer used by the Navy for primary training and is powered by a Pratt and Whitney PT-6 turboprop engine.

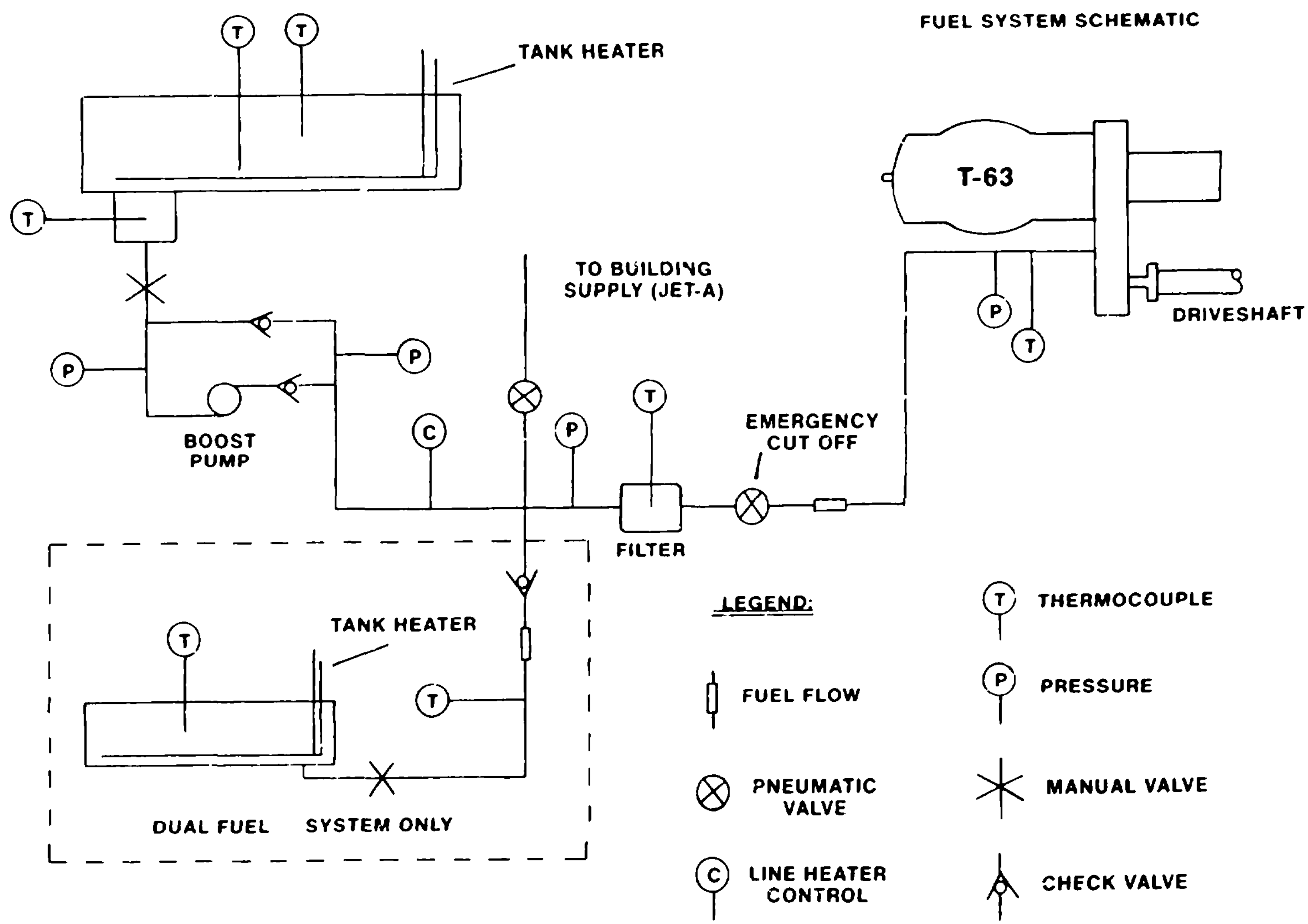


FIGURE 2. FUEL SYSTEM SCHEMATIC

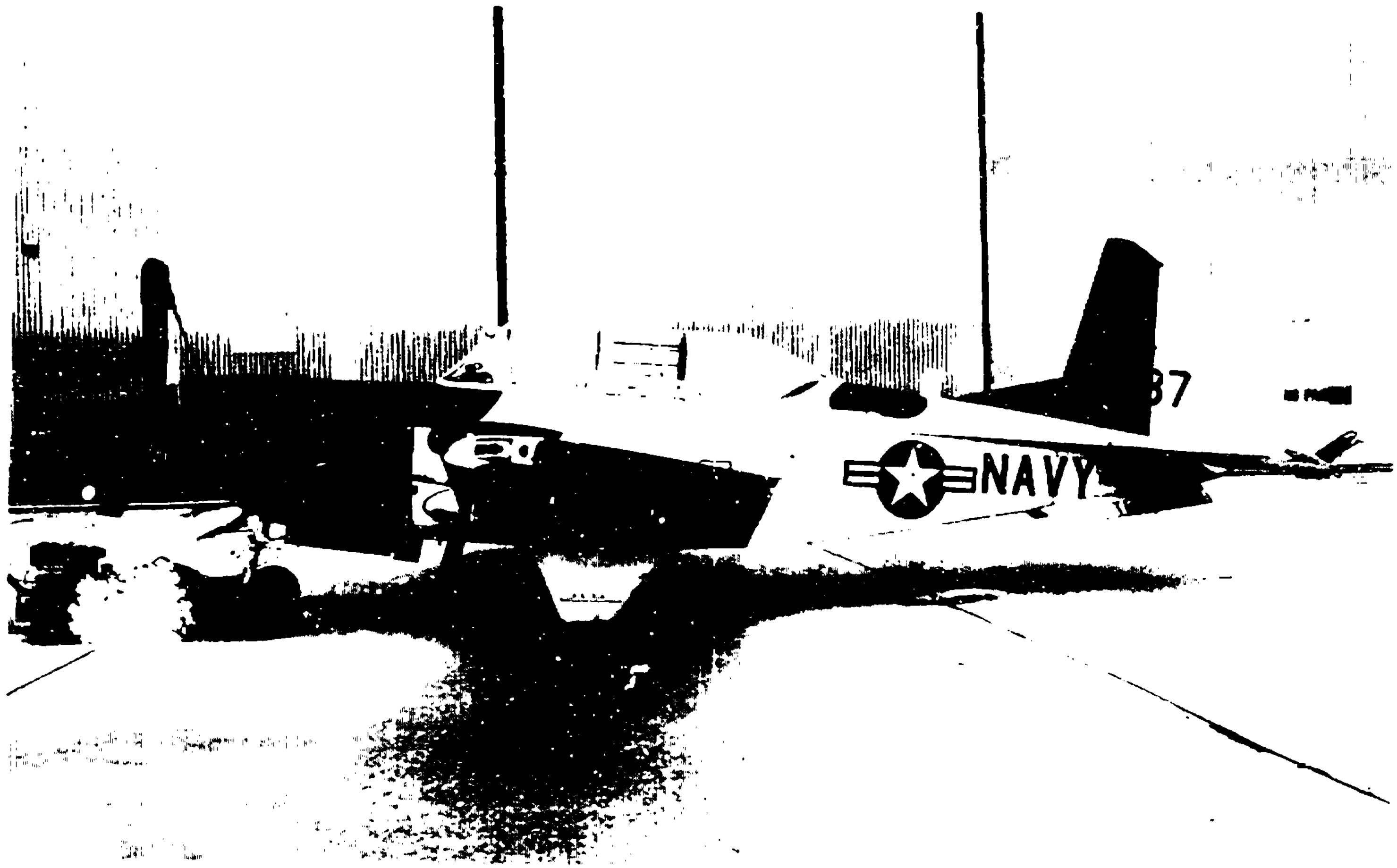
TABLE 1. TEST PARAMETERS

Parameter	Units
Ambient Temperature	°C
Barometric Pressure	mmHg
Boost Pump Inlet Pressure	Pa
Boost Pump Outlet Pressure	kPa
Burner Can Pressure	kPa
Compressor Discharge Pressure	kPa
Compressor Discharge Temperature	°C
Compressor Inlet Pressure	Pa
Compressor Inlet Temperature	°C
Dew Point	°C
Engine Driven Pump Inlet Pressure	kPa
Engine Driven Pump Outlet Pressure	kPa
Engine Oil Pressure	kPa
Engine Oil Temperature	°C
Fuel Flow, Secondary Tank Only	kg/hr
Fuel Flow, Total	kg/hr
Fuel Line Temperature	°C
Fuel Temperature, Boost Pump Inlet	°C
Fuel Temperature, Engine Driven Pump Inlet	°C
Fuel Temperature, Fuel Filter	°C
Fuel Temperature, Primary Tank	°C
Fuel Temperature, Secondary Tank	°C
Gas Generator Speed (N1)	percent
Oil Cooler Temperature	°C
Power Output Shaft Speed	rpm
Power Turbine Speed (N2)	percent
Tank in Use Indicator	dimensionless
Torque	N·m
Turbine Outlet Temperature	°C

Thermocouples were placed in key locations as indicated in figure 3. The filter housing temperature and the fuel pump temperature were measured using thermocouples which were glued to the exterior surface of the component. The temperatures were displayed in the cockpit and recorded by an observer. The ambient air temperature, pressure altitude, and indicated air speed were recorded from the existing aircraft instruments.

TEST PROCEDURES

Throughout the test program, the power lever of the test engine was fixed so that the maximum shaft speed was limited to 5,000 rpm. The dynamometer itself was then adjusted to maintain a maximum shaft speed of 4,850 rpm. This allowed the operator to establish the full range of turbine outlet temperatures (TOT) with the gas generator lever and without exceeding the dynamometer limitations.



Legend:

1. Forward Cowl Temperature
2. Lower Cowl Temperature
3. Fuel pump (air temperature)
4. Fuel Filter housing
5. Upper Cowl Temperature
6. Display

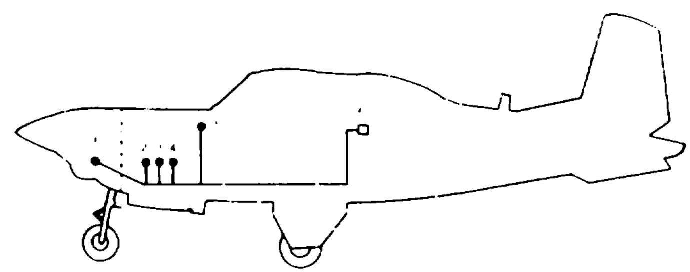


FIGURE 3. T-34 THERMOCOUPLE INSTALLATION

Except as noted, the engine was started on the building supply fuel system (Jet-A) and allowed to warm prior to collecting data. When the test required switching between fuels, the engine was operated for 3 minutes prior to continuing. This allowed all traces of the first test fuel to be purged from the system and prevented biasing the results.

All the ASTM tests were conducted in accordance with the appropriate test procedure. The Reid Vapor Pressure of the fuel samples that contained alcohol was determined using the dry method as outlined by ASTM.

BASELINE TESTS.

Baseline tests were conducted on all the test fuels used during the program. Jet-A was tested periodically throughout the program to monitor changes in the operation of the engine which might have occurred. During the initial Jet-A test, the engine was operated on the building supply system, on the primary fuel tank with the boost pump operational, and on the primary fuel tank with the boost pump off to establish that the supply system did not affect engine performance. The following summarize the baseline procedures that were used:

1. Start the automatic data acquisition system. Switch to the test fuel as appropriate.

2. Establish a turbine outlet temperature from the following list and allow conditions to stabilize.

TOT
538 °C (1000 °F)
579 °C (1075 °F)
620 °C (1148 °F)
663 °C (1226 °F)
693 °C (1280 °F)
721 °C (1330 °F)
749 °C (1380 °F)

3. Repeat item 2 until all the settings listed above have been tested.

4. Establish a TOT of 749 °C (1380 °F), then select the ground idle power setting.

5. Once conditions stabilized at the ground idle setting, select the takeoff power setting (TOT = 749 °C (1380 °F)).

6. Shut down the engine. Allow the engine to sit for 2 minutes, then conduct a start sequence using the test fuel.

HOT FUEL TESTS.

The initial test procedures for the hot fuel testing were modeled after those used in the Technical Center's autogas evaluations, reference 2. The transient response behavior of the turbine engine proved to be substantially different than the transient response behavior of the piston engine used in those studies. The hot fuel tests that are summarized below incorporate measuring the transient response of the engine on the test fuel:

1. Heat the test fuel to the desired temperature, draw a sample, then start the engine.

2. Establish a ground idle condition and select the test fuel. If necessary turn the electrically driven boost pump and electrical line heaters off. Monitor the engine operation for 5 minutes.

3. Set the controllers for the electrical line heaters to a setting of 150 °C or higher. Monitor the engine operation for 10 minutes.

4. Repeat steps 2 and 3 using a TOT of 749 °C (1380 °F).

5. Set the electrical line heaters to 150 °C (300 °F) or higher. Select the ground idle power setting.

6. After the engine has stabilized at the ground idle condition (minimum of 2 minutes), select the takeoff power setting TOT = 749 °C (1380 °F).

ENDURANCE RUNS.

These runs were designed to simulate a normal flight profile and were used to evaluate potential cumulative effects of the test fuels. The endurance runs were conducted as follows:

1. Start the engine on the test fuel and allow the engine to reach normal operating temperatures. Turn the boost pump off.

2. Select the takeoff power setting. Maintain this setting for a minimum of 15 minutes.

3. Select a power setting which results in a TOT between 660 °C (1240 °F) and 720 °C (1330 °F). Maintain this setting from 30 minutes to 3 hours.

4. Set the power to attain a TOT of 600 °C (1110 °F). Maintain this setting for a period of time equivalent to the time takeoff power was maintained at the start of the run.

5. Operate the engine at a ground idle setting for a minimum of 2 minutes.

DUAL FUEL SYSTEM TESTS.

Two fuels were used during the dual fuel system tests. Either ethanol or methanol was placed in the secondary tank and Jet-A was placed in the primary tank. The baseline and endurance tests were conducted with hot Jet-A and cold alcohol, hot alcohol and cold Jet-A, both fuels hot, and both fuels cold. The hot fuel tests were conducted with hot Jet-A and cold alcohol, hot alcohol and cold Jet-A, and both fuels hot. At the conclusion of these evaluations, 5 percent water was added to the alcohol and various operating conditions were evaluated.

TEST FUELS.

The Jet-A used in this program was from the same lot, and this fuel met the specifications outlined in American Society for Testing and Materials (ASTM) D-1655 (reference 3). Likewise, the JP-4 used in this program was drawn from the same lot. Anhydrous ethanol and methanol were used throughout the program. These were stored in sealed 208-liter (55 gallon) barrels until needed.

The alcohol concentrations presented in this report are calculated on a weight/weight basis; that is, the weight of the alcohol divided by the weight of the final mixture.

During the hot fuel tests, the water content of the test fuels varied as the temperature of the base fuel varied, whenever the barrel of alcohol was changed, and as alcohol was drawn from the barrel. Water was added to all the fuels used in the hot fuels tests to compensate for these changes. Typically, the water concentration was adjusted to between 0.1 to 0.15 percent on a weight/weight basis.

Typically, Reid Vapor Pressures (RVP) were determined using the procedures for the wet method as outlined in ASTM Standard D-323. If the fuel contained any alcohol, the RVP was determined using the dry method as described in D-323.

T-34 FLIGHT TESTS.

Four flight profiles were flown with the T-34 aircraft with the intention of looking at a range of operations for conditions which might result in the hottest operating temperatures. These flights were conducted at the FAA Technical Center, Atlantic City International Airport, NJ. The field elevation is 23 meters (76 feet) above mean sea level.

PROFILE 1 - TRAINING. These flights consisted of a takeoff; a climb to an altitude between 900 and 1500 meters above ground level (3,000 and 5,000 feet); a 10 minute cruise; a period of flight where various maneuvers such as slow flight, stalls, steep turns, and chandelles are performed; a descent; a full-stop landing; a shutdown; a restart when the cowling temperatures peaked, and 5 touch-and-go operations.

Temperature readings were taken during each maneuver. If a maneuver lasted more than a couple minutes (e.g., during the 10 minute cruise), temperature readings were taken at the beginning and end of the maneuver. Readings were taken during the ground roll, climb, pattern, descent, and rollout portions of the touch-and-go phase of these flights.

PROFILE 2 - STEP CLIMB. These flights consisted of the following: a takeoff and climb to a pressure altitude of 762 meters (2,500 feet), and a 10-minute cruise at 75 percent torque. The pressure altitude was then increased in steps of 762 meters (2,500 feet), until a pressure altitude of 3,810 meters (12,500 feet) was reached. A 10-minute cruise using 75 percent torque was established at each altitude. A descent to landing followed the cruise portion at 3810 meters (12,500 feet).

Temperature readings were taken during ground operations, the climb portion of each step, at the beginning and end of each cruise period, at 762-meter (2,500 feet) intervals during the descent, and during the pattern, approach, and roll-out phase of the landing.

PROFILE 3 - MAXIMUM PERFORMANCE CLIMB. The takeoff was followed by a climb at the best rate of climb airspeed to a pressure altitude of 3,810 meters (12,500 feet). The cruise portion of the flight included periods of operation at 60 percent torque and at 75 percent torque.

Temperature readings were taken during ground operations, at pressure altitude increments of 762 meters (2,500 feet) during both climb and descent, at the start and conclusion of each cruise segment, and during the pattern, descent, and roll-out of the landing.

PROFILE 4 - CRUISE CLIMB. All operations are as described in the maximum performance climb profile, with the exception of the airspeed used during the climb to altitude. In this case, the airspeed was maintained at 120 knots indicated while in the climb configuration.

RESULTS

Unless stated otherwise, the data reported in this section have been corrected to standard temperature and pressures using the procedure described in the T-63 overhaul manual's run-in and test procedures. These procedures also correct for changes in energy density and specific gravity. Appendix A presents the data contained in figures 4, 5, 6, and 7 in more detail.

BASELINE TESTS.

The initial series of engine tests, conducted with Jet-A, were intended to demonstrate system repeatability over a broad range of ambient conditions. The initial results showed a 15 percent scatter in power developed and a 10 percent scatter for the fuel flow, when presented as a function of TOT. A review of the data indicated the exhaust gas was being re-ingested, so a ducted inlet was installed and the series of tests was repeated. Following this modification the power developed and fuel flow were repeatable within 3 percent of the reading. The break specific fuel consumption data fell within 1 percent of the reading with the exception of very low power settings and transient operations.

The power developed when operating on neat JP-4 and 100LL avgas was within system repeatability of the power developed with Jet-A. The uncorrected fuel consumption was slightly higher than with Jet-A, and this reflected the difference in specific gravity. When the specific gravity and energy density were taken into consideration, the fuel flow was within system repeatability of the Jet-A data.

JET-A/ETHANOL BLENDS. Figure 4 shows the power developed as a function of turbine outlet temperature for neat Jet-A and a number of Jet-A/ethanol blends. The power developed with neat Jet-A is consistently higher than the power developed with the Jet-A/ethanol blends. There is no clear pattern among the Jet-A/ethanol data to indicate a concentration effect.

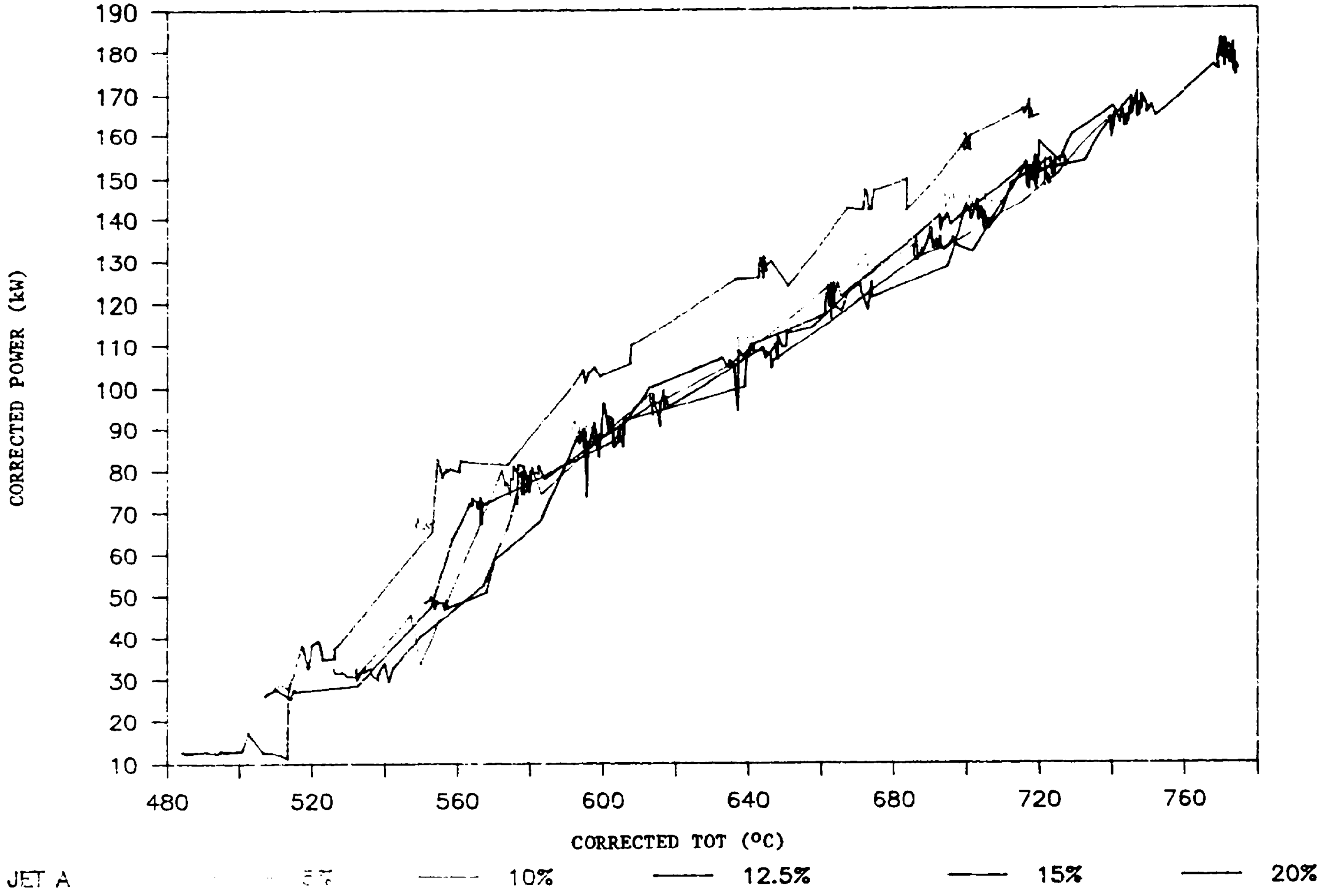


FIGURE 4. CORRECTED POWER DEVELOPED VERSUS CORRECTED TURBINE OUTLET TEMPERATURE FOR JET-A/ETHANOL BLENDS

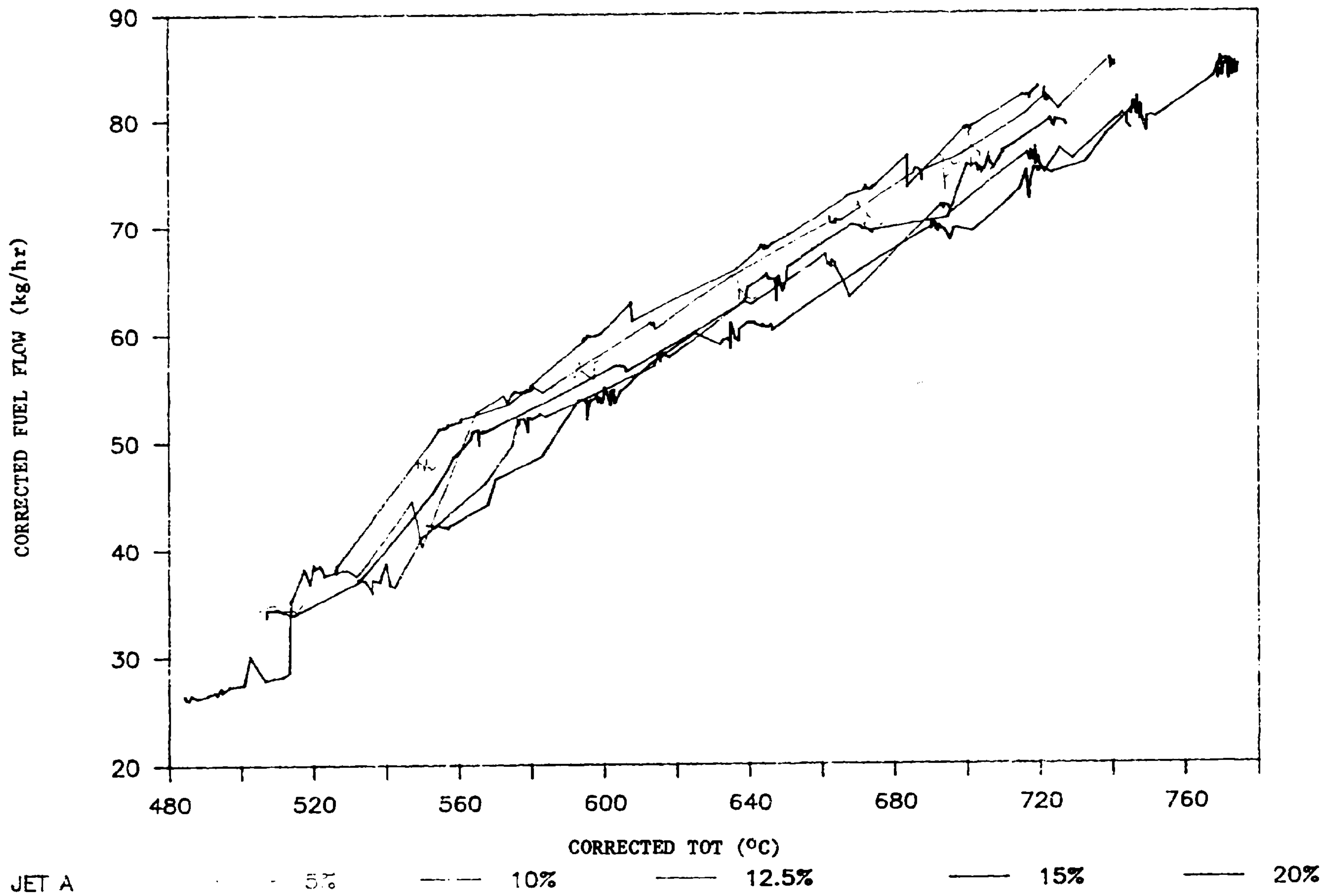


FIGURE 5. CORRECTED FUEL FLOW VERSUS CORRECTED TURBINE OUTLET TEMPERATURE FOR JET-A/ETHANOL BLENDS

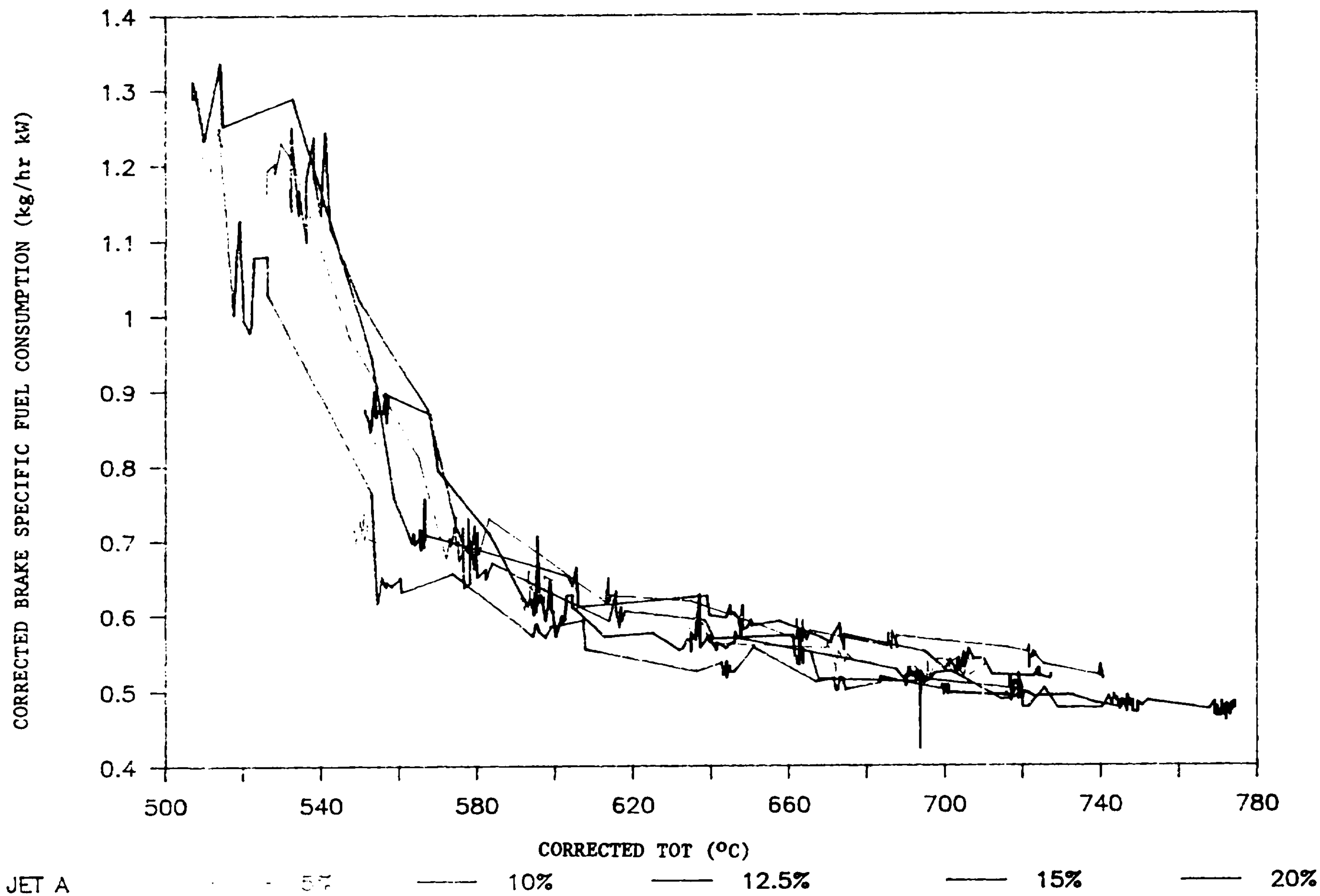


FIGURE 6. CORRECTED BRAKE SPECIFIC FUEL CONSUMPTION VERSUS CORRECTED TURBINE OUTLET TEMPERATURE

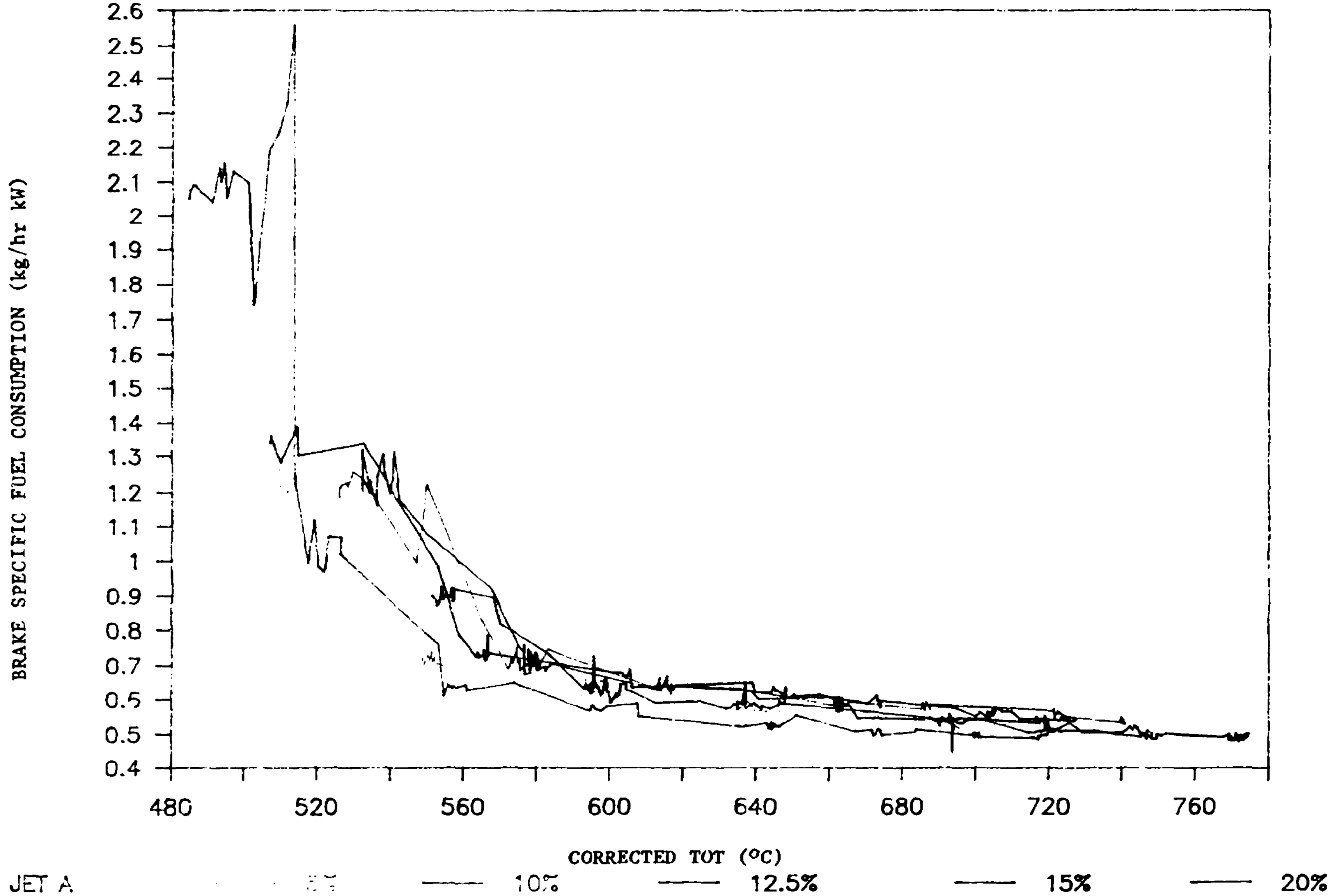


FIGURE 7. BRAKE SPECIFIC FUEL CONSUMPTION VERSUS CORRECTED TURBINE OUTLET TEMPERATURE

Figure 5 shows the corrected fuel flow as a function of TOT. (When reviewing this figure, keep in mind the corrections compensate for changes in the energy density.) In this case there is a general trend showing the fuel consumption declining as the concentration increases. The only exception to this trend is the 12.5 percent ethanol in Jet-A blend. This anomaly may be a consequence of the correction procedures which do not account for humidity, and the fact that the 12.5 percent data were obtained on an exceptionally cold, dry day. The combination of these plots indicates the flame front with the ethanol blends extends further into the burner can than the flame front with neat Jet-A, resulting in a higher TOT. This is consistent with the observations made at the Naval Air Propulsion Center when a T-63 was operated on various alcohol blends with an instrumented combustor (reference 4).

Figure 6 shows the corrected break specific fuel consumption (BSFC) as a function of TOT for neat Jet-A and various Jet-A/ethanol blends. It is interesting to note that even though the computations compensate for the energy density, the Jet-A data are consistently lower than the Jet-A/ethanol blends. There is no apparent trend among the different ethanol concentrations in this case. As seen in figure 7, there is an increase in fuel consumption as the alcohol concentration increases if data are not adjusted for energy density. In general, the data in figure 7 reflect the decrease in energy available as alcohol is added to the test fuel.

Transient response times were measured for the TOT, gas generator speed (N1), and power turbine speed (N2) when decelerating from takeoff to ground idle (decels) and accelerating from ground idle to takeoff power (accels) while operating on the different test fuels. These tests were conducted with the boost pump on to ensure vapor formation did not affect the results. In general, there was no difference in the engine response times, but there were problems in that the end point would not always be the desired setting. For example, when conducting an accel, the final TOT might be 700 ^{o}C (1290 ^{o}F) as opposed to the desired 749 ^{o}C (1380 ^{o}F). The problem was more severe the higher the ethanol concentration and if a hot ethanol blend was used during the previous test.

Transient response times were measured during the start sequence as well. In this case, there was a gradual increase in start times as the testing continued. In addition, the idle setting gradually decayed over time, eventually resulting in a gas generator speed of 55 percent as opposed to the normal 61 percent. This trend was observed with both the Jet-A/ethanol blends, JP-4/ethanol blends, neat JP-4, and neat Jet-A. Occasionally, a hung start would result, and multiple attempts were required to affect a start. The incidence of hung starts appeared to increase after conducting hot fuel tests with fuels that contained ethanol.

DUAL FUEL SYSTEM. The dual fuel system was evaluated with ethanol in the alcohol tank and Jet-A in the test fuel tank. The design goal for the dual fuel system called for no alcohol flow below the approach power setting and for an ethanol concentration of 10 to 12 percent under cruise conditions (TOT = 700 ^{o}C (1290 ^{o}F)). This resulted in a concentration of 15 to 18 percent at takeoff power settings (figure 8). The BSFC at a given power setting and under steady state conditions was within system repeatability for the same concentration of a Jet-A/ethanol blend.

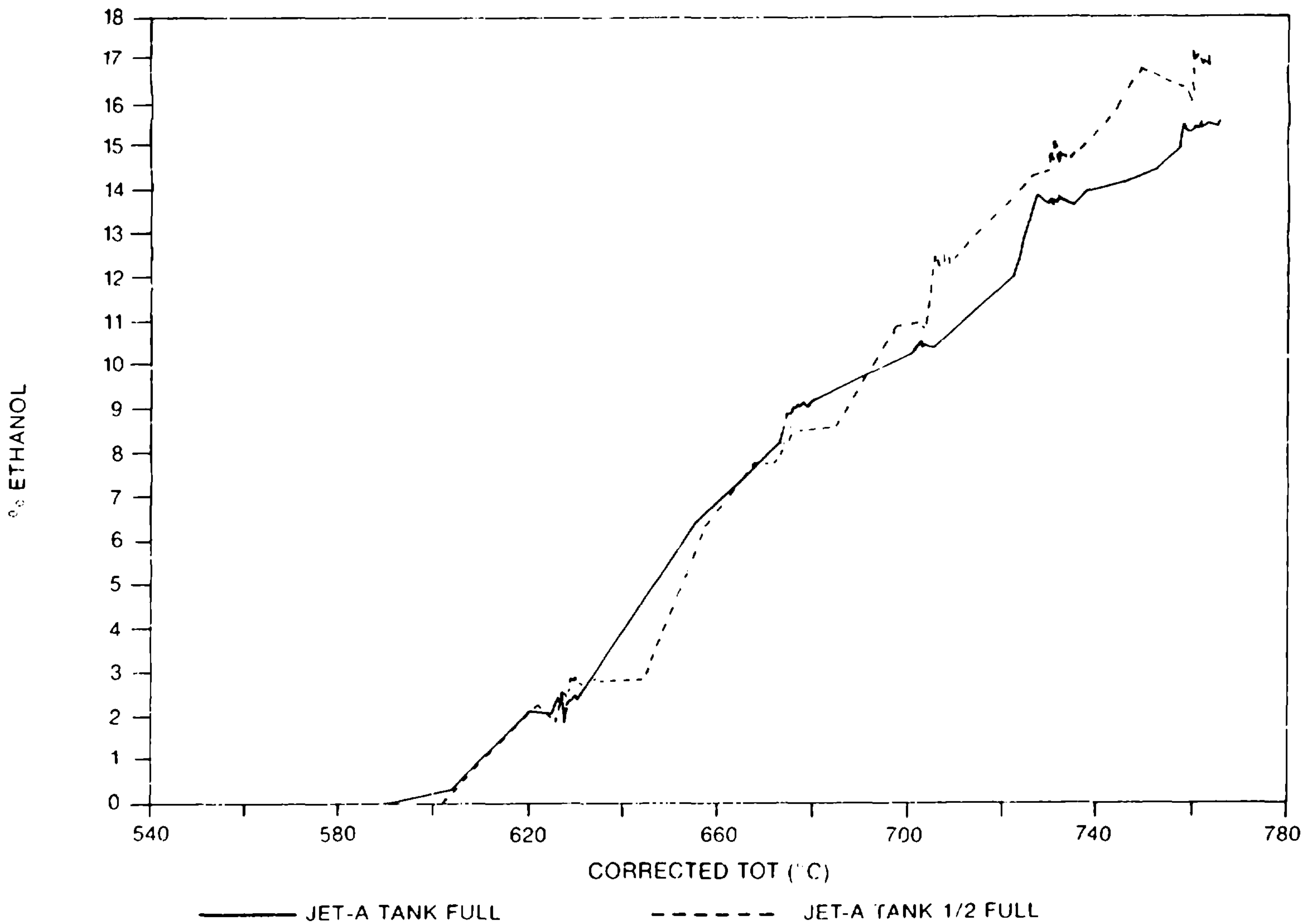


FIGURE 8. ALCOHOL CONCENTRATION VERSUS CORRECTED TURBINE OUTLET TEMPERATURE FOR DUAL FUEL SYSTEM

The transient response of the engine when using the dual fuel system was evaluated with the boost pump off. Even with this difference, the transient response time for the engine did not change as a consequence of operations on the dual fuel system. Also, the problems noted with hung starts, decaying idle speeds, and poor repeatability during transient operations with the alcohol blends appeared to stabilized with the use of the dual fuel system. This may be a consequence of purging the fuel system with neat Jet-A as part of normal operations with the dual fuel system.

Five percent water was added to a sample of ethanol, and this mixture was used in the dual fuel system configuration along with Jet-A. The power developed was normal for any given TOT when using this mixture but the fuel flow indicator did not work when the ethanol concentration was above approximately 5 percent. The fuel flow sensor used optics to measure the fuel flow, and the Jet-A/ethanol/water blend was too cloudy for the sensor to work properly.

NEAT ETHANOL. An attempt was made to operate the T-63 on neat ethanol. The engine would quit if ethanol was selected after the engine had been established on any condition other than a high idle (a TOT between 540 (1005 °F) and 570 °C (1060 °F)). Any attempt to accelerate out of the high idle condition or to reduce the idle setting would result in the engine quitting.

Attempts to restart the engine after it had shut down on neat ethanol required bleeding the entire fuel system. In addition, the low idle setting needed to be re-adjusted following the neat ethanol series, and problems with hung starts increased dramatically following these tests.

JET-A/METHANOL BLENDS. The Jet-A/methanol blends were unstable and phase separation occurred following minimal handling. As a consequence, Jet-A/methanol blends were not used as part of the testing. An attempt was made to see if operations using methanol in the dual fuel system were possible. While the power developed and BSFC were within the expected ranges, the fuel flow indications were unreliable when more than 2 percent of the total flow was methanol. A short test was conducted with a 50/50 mixture of methanol and tertiary-butyl alcohol (TBA). TBA is used as a co-solvent when methanol is blended with automobile gasoline, and the use of TBA allowed for the use of methanol without affecting the fuel flow indications.

HOT FUEL TESTS.

The Technical Center was unable to induce fuel starvation when testing neat Jet-A in the dynamometer installation. Fuel temperatures as high as 82 °C (180 °F) were recorded during this series of tests. Tests with neat JP-4 indicate that a fuel temperature of 46 °C (115 °F) to 49 °C (120 °F) is the most likely to result in fuel starvation during hot fuel certification. Hot fuel testing was also conducted with 100LL avgas. In this case, a temperature of 43 °C (110 °F) to 46 °C (115 °F) was the most likely to result in vapor lock.

JET-A/ETHANOL BLENDS. The Jet-A/ethanol blends were tested with a tank fuel temperature ranging from 21 °C (70 °F) to 52 °C (125 °F), and with ethanol concentrations up to 20 percent. At the conclusion of each test, arbitrary point values were assigned depending on the fuel system/engine's response to the different test conditions. The tallies presented in table 2 allow a quick summary of the test variables which will most likely result in fuel starvation during hot fuel certification tests. The engine driven pump inlet pressure, at the time the engine quit, is listed in the appropriate box in table 2.

With the exception of the 12.5 percent ethanol in Jet-A blend, no variations in any of the fuel system parameters were noted when the temperature of a Jet-A/ethanol blend was 45 °C (113 °F) or lower. A surge was noted when accelerating from idle to takeoff with a 12.5 percent ethanol in Jet-A blend with a fuel temperature of 41 °C (105 °F) (note: the 41 °C (105 °F) surge is included in the 12.5 percent ethanol in the Jet-A tally and in the accel tally). Likewise, the 12.5 percent ethanol in Jet-A blend was the only fuel to exhibit a fuel related operational problem during the decel portion of the tests. It should be noted that the engine quit during a decel test with a 10 percent ethanol in Jet-A blend, but the data indicated it may have been the consequence of the fuel controller calling for too low of an idle setting. This problem is probably related to the other fuel control related difficulties noted above.

The accelerations are clearly the most critical operational mode. This may be a consequence of the significantly higher fuel flows required during the acceleration mode. A review of the data indicates the fuel controller calls for roughly a 50 percent higher fuel flow during the acceleration mode when compared with the steady state takeoff setting.

The water content may also play a role in determining if fuel starvation will occur. Early in the test sequence with the Jet-A/ethanol blends, no water was added to test fuel. It was noted that some of the fuel related problems, such as fuel pressure fluctuations, appeared to be worse if the water content was relatively high. The water content of all the fuels after that point was adjusted so that the phase separation temperature was about 15 °C (60 °F). This avoided the phase separation problems that could have occurred as the fuel was handled at room temperature.

The RVP of the base Jet-A was 6.7 kilo-Pascal (kPa) or 1 pound per square inch (psi). When ethanol was added, the RVP increased to between 12.8 to 15.2 kPa (1.9 to 2.2 psi). The magnitude of the RVP increase appeared to be independent of the alcohol and water concentrations over the ranges tested. There were no significant differences between the pre- and post-test RVP data. It should be noted that the RVP of the samples which contained alcohol were determined with the dry method.

TABLE 2. SUMMARY OF JET A/ETHANOL TESTS

Point Values: Significant = 1
Surge = 5
Quit = 10

Repeat Points Averaged

FUEL	46°C STEADY STATE	46°C DECEL	46°C ACCEL	52°C STEADY STATE	52°C DECEL	52°C ACCEL	NOTES:
Jet-A	No Evidence (0)	No Evidence (0)	No Evidence (0)	No Evidence (0)	No Evidence (0)	No Evidence (0)	Tally = 0
5% Ethanol in Jet-A	No Evidence (0)	No Evidence (0)	Surged; No Evidence on Retest (2.5)	No Evidence (0)	No Evidence (0)	Surged (5)	Tally = 7.5
10% Ethanol in Jet-A	No Evidence (0)	No Evidence (0)	Quit -20 kPa (10)	Significant at Takeoff and Idle (2)	No Evidence (0)	Quit -15 kPa (10)	Tally = 22
12.5% Ethanol in Jet-A	Significant at Idle (1)	No Evidence (0)	Quit -22 kPa (10)	Significant at Takeoff and Idle (2)	Significant (1)	Quit -15 kPa (10)	Surged 41°C Accel (5) Tally = 29
15% Ethanol in Jet-A	No Evidence (0)	No Evidence (0)	Quit -20 kPa (10)	Significant at Takeoff (1)	No Evidence (0)	Quit -15 kPa (10)	Tally = 21
20% Ethanol in Jet-A	No Evidence (0)	No Evidence (0)	Significant (1)	No Evidence (0)	No Evidence (0)	Quit -17 kPa (10)	Tally = 11
	Tally for 46°C = 34.5			Tally for 52°C = 51			

Accel Tally = 83.5
Steady State Tally = 6
Decel Tally = 1

JP-4/ETHANOL BLENDS. Based on the results obtained with gasoline/alcohol blends, which show 15 percent ethanol as the critical concentration for hot fuel certificatioı reference 5), and the Jet-A/ethanol blends above, a concentration of 12.5 percent ethanol in JP-4 was tested over a range of temperatures from 38 °C (100 °F) to 52 °C (125 °F). Table 3 shows the results of these tests. As with the ethanol/Jet-A blends, an acceleration with a fuel temperature of 52 °C (125 °F) was the most likely condition to result in fuel starvation. The RVP of the pre- and post-test samples varied from 18.6 to 20 kPa (2.7 to 2.9 psi), which is not significantly different from the RVP of the base JP-4 (20.7 kPa or 3.0 psi).

TABLE 3. SUMMARY OF THE 12.5 PERCENT ETHANOL IN JP-4 TESTS

Fuel Temperature	Steady State Results	Deceleration Results	Acceleration Results
38 °C (100 °F)	No Evidence	No Evidence	Significant Variations in Fuel Flow and Pressure
43 °C (110 °F)	No Evidence	No Evidence	Hesitated
46 °C (115 °F)	Some Variations in Fuel Flow and Pressure	No Evidence	Surged then Quit
52 °C (125 °F)	Some Variations in Fuel Flow and Pressure	No Evidence	Quit

Following these tests, the concentration was varied while the temperature of the test fuel was maintained at 52 °C (125 °F). These tests were conducted with a different batch of JP-4. In this case, the RVP varied from 29 to 30.3 kPa (4.2 to 4.4 psi) and, as a consequence, the behavior of the fuel was significantly worse. With these test fuels, fuel starvation was regularly encountered at takeoff power under steady state conditions. Table 4 lists the time-to-fuel starvation and the fuel temperatures in the tank sump, in the filter housing, and at the engine driven pump inlet when the engine quit. The same parameters are listed when fuel pressure fluctuations were encountered under steady state idle conditions. In general, the results are very similar for all the concentrations tested. Indeed, the temperature of the fuel in the tank sump appeared to have more effect on the times listed than did the ethanol concentration.

It should be noted that operations using hot JP-4/ethanol blends were more likely to result in fuel starvation than operations using hot Jet-A/ethanol blends.

TABLE 4. SUMMARY OF JP-4/ETHANOL TESTS

Ethanol Conc. (%)	Takeoff Power setting+ Time (min)	Sump (°C)	Filter (°C)	Pump (°C)	Idle power setting* Time (min)	Sump (°C)	Filter (°C)	Pump (°C)
10	8.83	51.4	56.0	54.0	13.50	49.7	63.0	59.0
12.5	8.67	51.3	55.0	54.0	12.33	48.0	63.0	58.0
15	9.33	51.3	57.0	54.0	12.00	51.4	60.0	57.0
20	7.17	52.6	54.0	52.0	12.67	49.4	65.0	62.0

+ time and temperatures when engine quit
* time and temperatures when fuel flow and pressure fluctuations began

DUAL FUEL SYSTEM. Different combinations of tank temperatures were tried with the dual fuel system; for example, hot ethanol and cold Jet-A, hot Jet-A and cold ethanol, etc. The condition most likely to result in fuel starvation was the use of both hot Jet-A and hot ethanol. At takeoff power and under steady state conditions, there were significant fluctuations in the fuel flow indications when both the Jet-A and ethanol were maintained at 52 °C (125 °F). In general these fluctuations were larger than those noted with the Jet-A/ethanol blends. These fluctuations did not affect the engine operations, however. The engine did not quit during accelerations with the 52 °C (125 °F) fuel in the dual fuel system even after repeated attempts to force the engine to quit. Under these conditions, the fuel flow lagged and there was a slight audible surge, but the engine continued to accelerate without pause (figures 9 and 10). Use of the Jet-A/ethanol blends under the same conditions resulted in either significant surges which required the engine being shut down or the engine quitting.

There was a concern that the use of cold fuel might result in solubility problems which would result in more operational problems than the hot fuel condition in the dual fuel system configuration. Two tests were conducted to evaluate the dual fuel system with cold fuel. The fuel was chilled to 0 °C (32 °F) and -14 °C (7 °F), and the engine operated over the full range of conditions including acceleratons and decelerations. No operational problems were encountered in these tests.

JET-A/METHANOL. Hot fuel tests were conducted using methanol and Jet-A in the dual fuel configuration and with the fuel in the tanks heated from 41 °C (106 °F) to 52 °C (125 °F). The concentration at idle was adjusted to an estimated 12.5 percent (since the fuel flow indications were unreliable, the total fuel flow was estimated from past data). At takeoff, the concentration was allowed to stabilize at the nominal 15 percent that normally occurred with the dual fuel system. At all the test temperatures, the engine quit due to fuel starvation at the takeoff power setting. In general, the hotter the fuel in the tank, the sooner fuel starvation occurred. With the 52 °C (125 °F) test fuel, the engine quit prior to turning on the line heaters. This behavior is substantially worse than the behavior of the Jet-A/ethanol blend that resulted when ethanol was used in the dual fuel system.

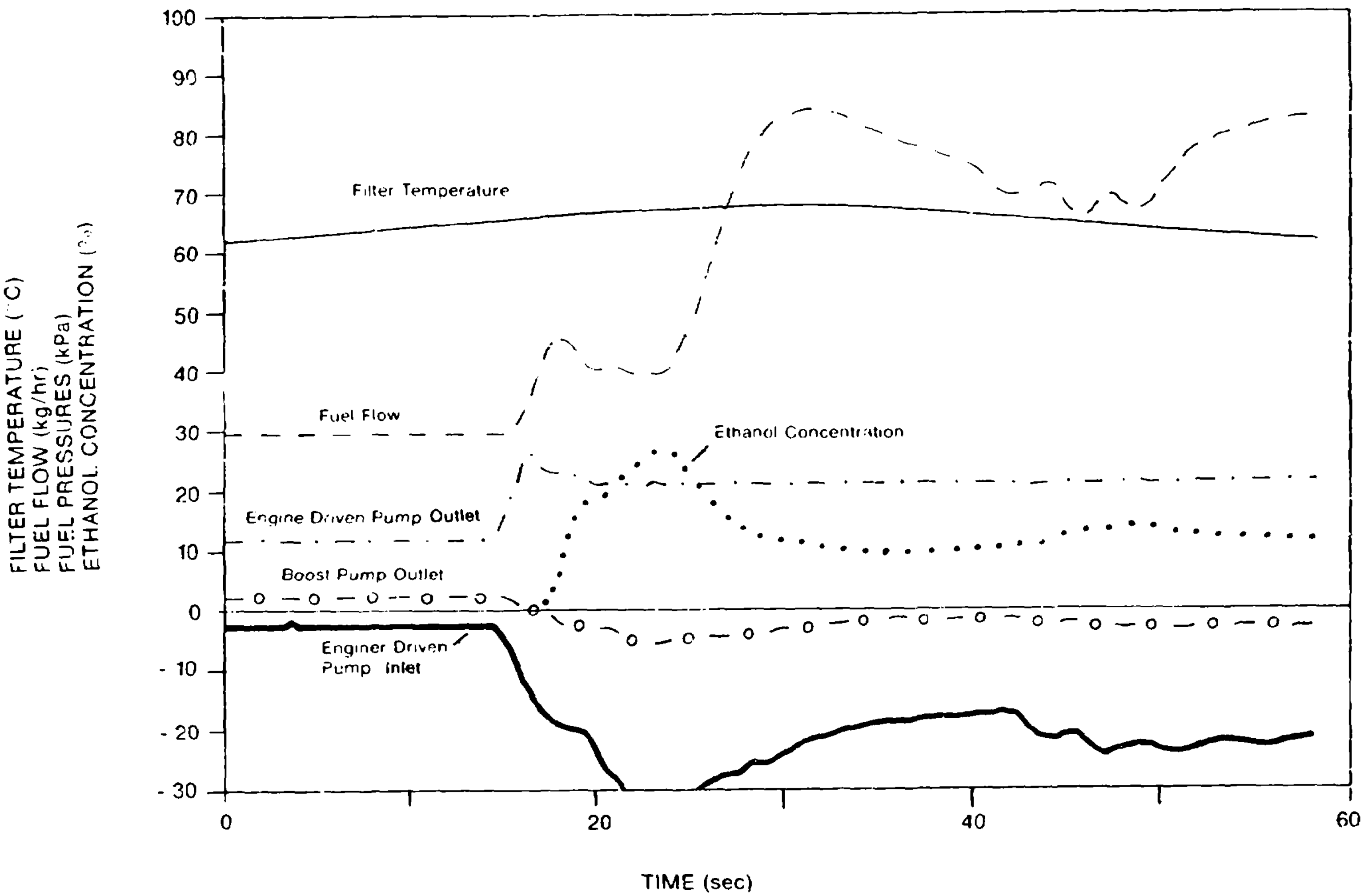


FIGURE 9. DUAL FUEL SYSTEM PARAMETERS DURING AN ACCELERATION

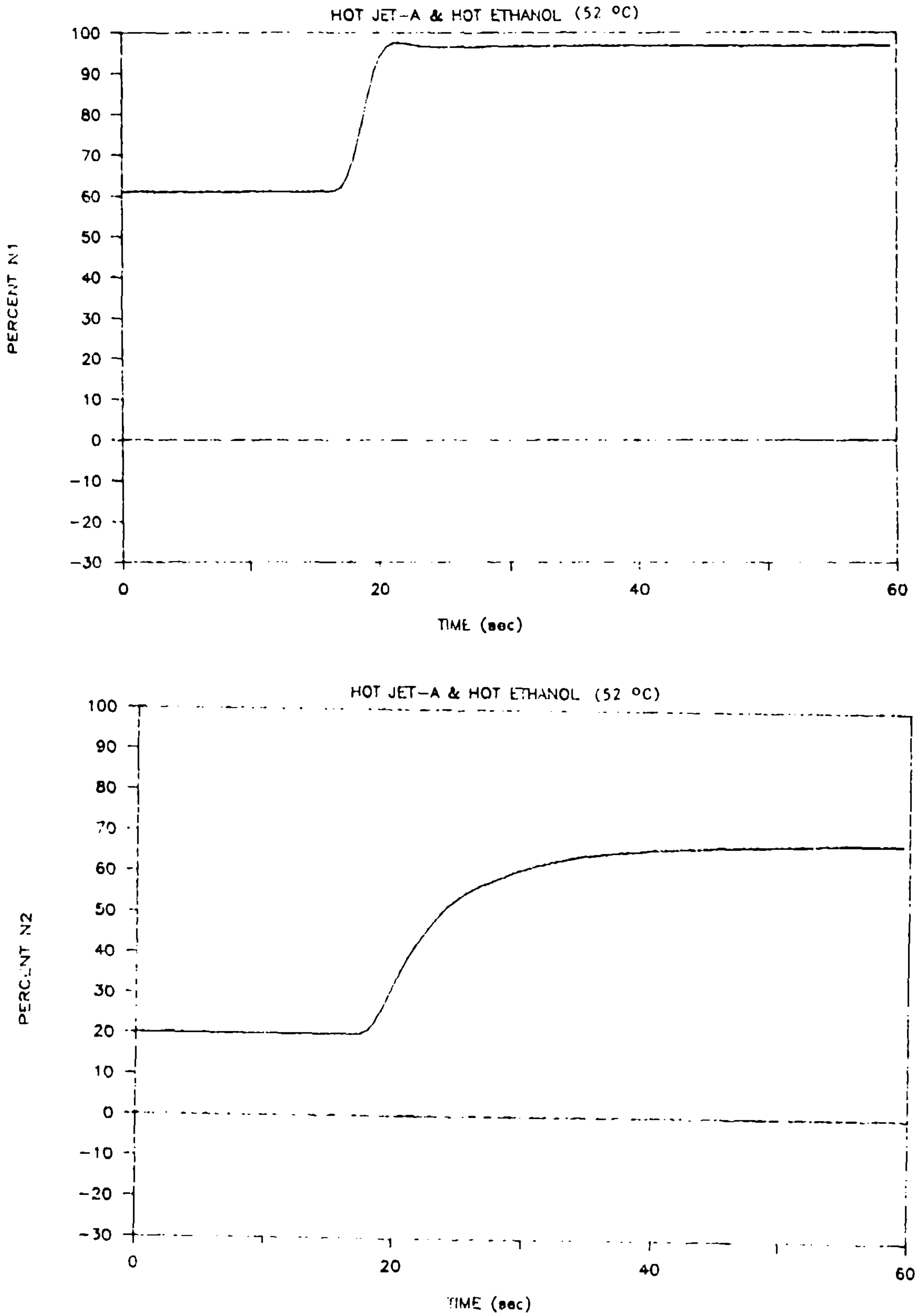


FIGURE 10. TURBINE SPEED VERSUS TIME DURING AN ACCELERATION USING THE DUAL FUEL SYSTEM

Due to the instability of the Jet-A/methanol blends, no hot fuel tests were conducted with this class of fuel. Likewise, no runs were attempted with straight methanol due to low energy content of methanol.

RELATED OBSERVATIONS.

A sample of 12.5 percent ethanol in Jet-A was intentionally contaminated with enough water to result in some phase separation. During the course of the run, small amounts of the water-rich phase, which settled to the bottom of the tank, would be ingested into the engine. Whenever this occurred, the engine would surge.

As the water was first added to the Jet-A/ethanol blend, the drops from the pipette would grow as they settled; then they would rise. As more water was added, the droplets would grow as they settled and leave a trail of density waves behind. When the blend was close to saturation, the density waves would persist for an extended period of time. If the sample was left to stand overnight, the container would stratify with the upper half having a large number of density waves and the lower half being clear. A sample which was drawn from the upper half of the tank contained 15 percent ethanol. The lower half contained only 5 percent ethanol. Once enough water was added to the sample, the water-rich phase would settle to the bottom of the container. Heating the sample would drive the water into solution.

Initially, several starts were attempted with increasing ethanol concentrations. It was noted that as the ethanol concentration increased, the starts became more difficult. This agrees with observations made at the Naval Air Propulsion Center (reference 4). This problem was independent of the hung starts which occurred as a result of the material compatibility problem, noted above.

The exhaust smelled sweet when the T-63 was operating with methanol during the dual fuel system tests. The exhaust had a distinctive odor when the test fuel contained methanol and TBA. The use of ethanol did not appreciably change the odor of the exhaust.

T-34 FLIGHT TESTS.

During the profile 1 flights, a number of different maneuvers were flown. These included climbs at the best rate of climb airspeed, steep turns, ground reference maneuvers, lazy eights, chandelles, and slow flight. In general, the temperatures recorded did not vary significantly except for the forward cowling temperature which was highest during the slow flight maneuvers. A series of touch-and-go operations were also performed as part of the profile 1 series. In general, the temperatures were higher during this portion of the profile than during the preceding flight maneuvers. Figure 11 shows the temperature history during a typical touch-and-go sequence. The letter "T" indicates the takeoff roll, "P" indicates the pattern segment, and "A" denotes the approach portion of the sequence. The temperature in the forward area is significantly higher during the approach segment since the bleed air is open at the reduced power setting. In general, the fuel system components are hottest during the approach and beginning of the takeoff roll. The overall trend downward throughout the sequence in figure 11 is a consequence of the fact the sequence was flown following a hot soak.

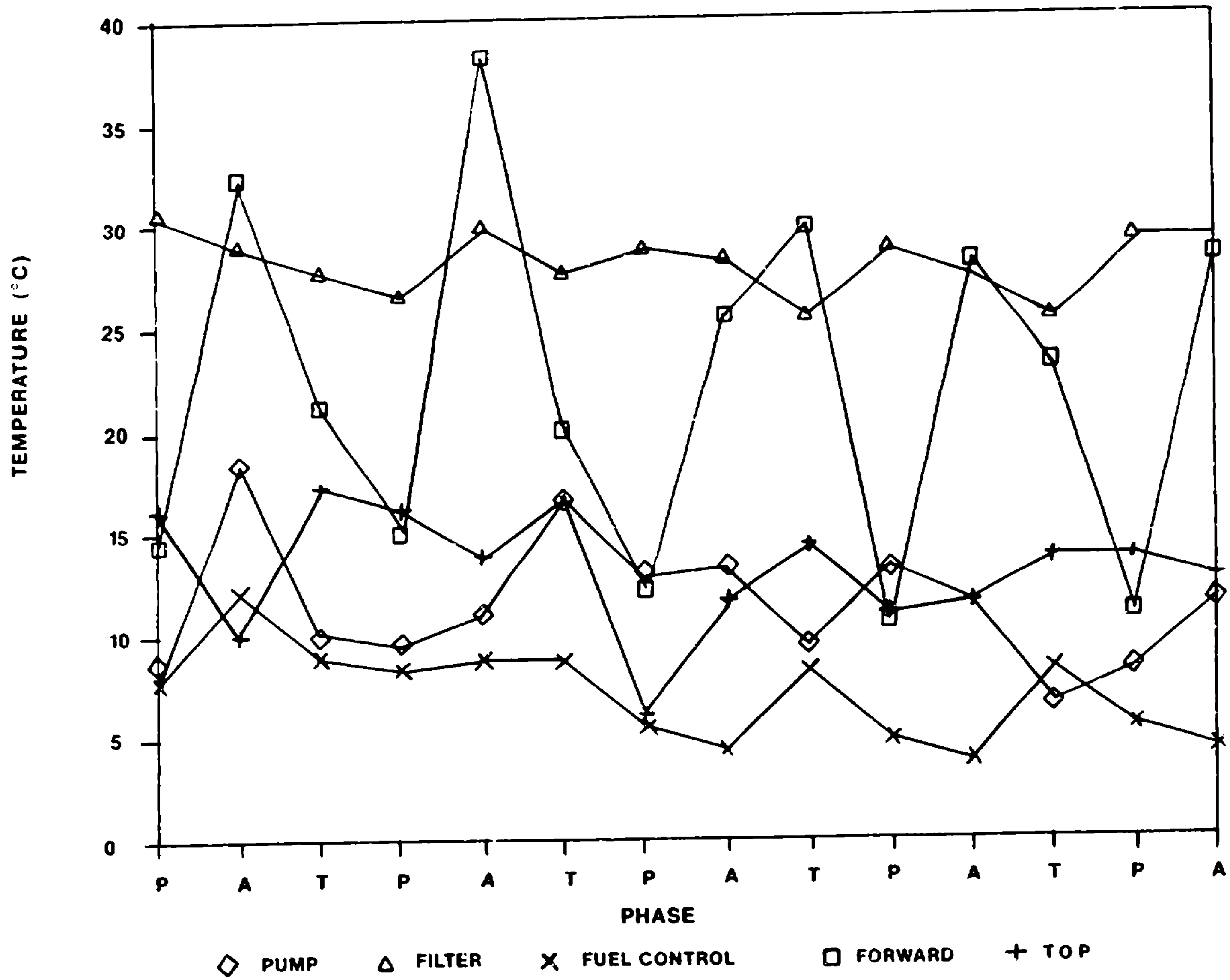


FIGURE 11. TEMPERATURE PROFILE FOR A TOUCH-AND-GO SEQUENCE

During the step climb (profile 2), the fuel system temperatures tended to peak shortly after the power reduction at each altitude. They would then stabilize at approximately the temperatures found when the aircraft first reached that altitude. The temperatures recorded during the descent were the same or lower than the temperatures recorded during the climb and cruise portion of this profile.

Overall, there was not a significant difference between using the airspeed which yielded the best rate of climb (profile 3) and the cruise climb configuration (profile 4). Figure 12, which shows the ascent portion of a profile 3 flight, is typical. As with the step climb profile, the temperatures recorded during the descent were the same or lower than the temperatures recorded during the ascent. The temperature increase which occurs toward the end of figure 12 is a consequence of increasing the power setting from 65 to 70 percent of maximum continuous power.

The average difference between the various fuel system temperatures and the ambient temperature for profiles 3 and 4 is presented in figure 13. In general, the system temperatures track with the ambient temperature. The only exception is the temperature of the fuel filter housing. The lower filter temperatures associated with ground operations (SL in figure 13) are attributable to the fact that the fuel is cold during the initial start sequence and the fuel in the wings remains cool following descent. This shows that the change in air density with altitude has a minimal effect.

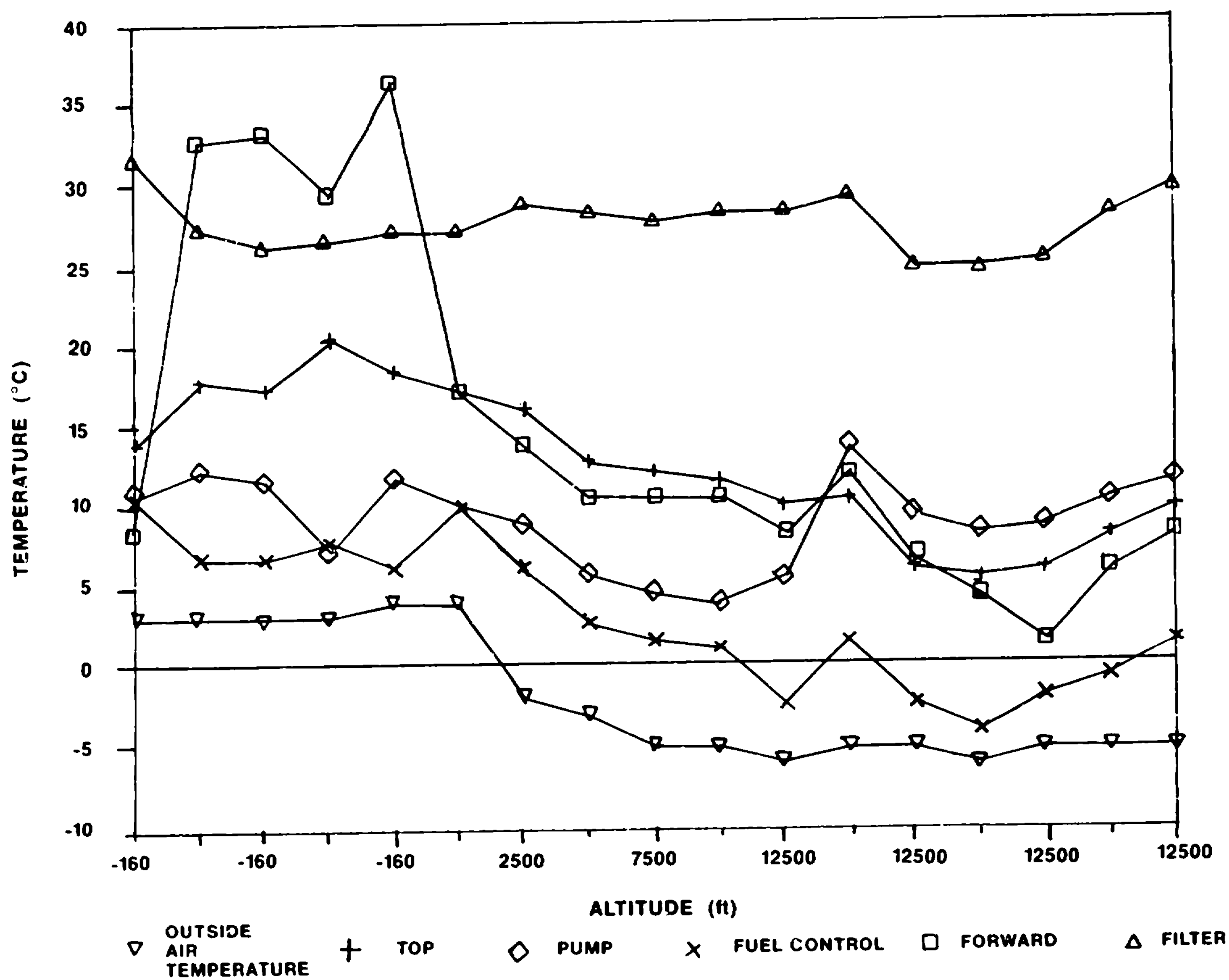


FIGURE 12. TEMPERATURE PROFILE FOR A MAXIMUM RATE OF CLIMB ASCENT

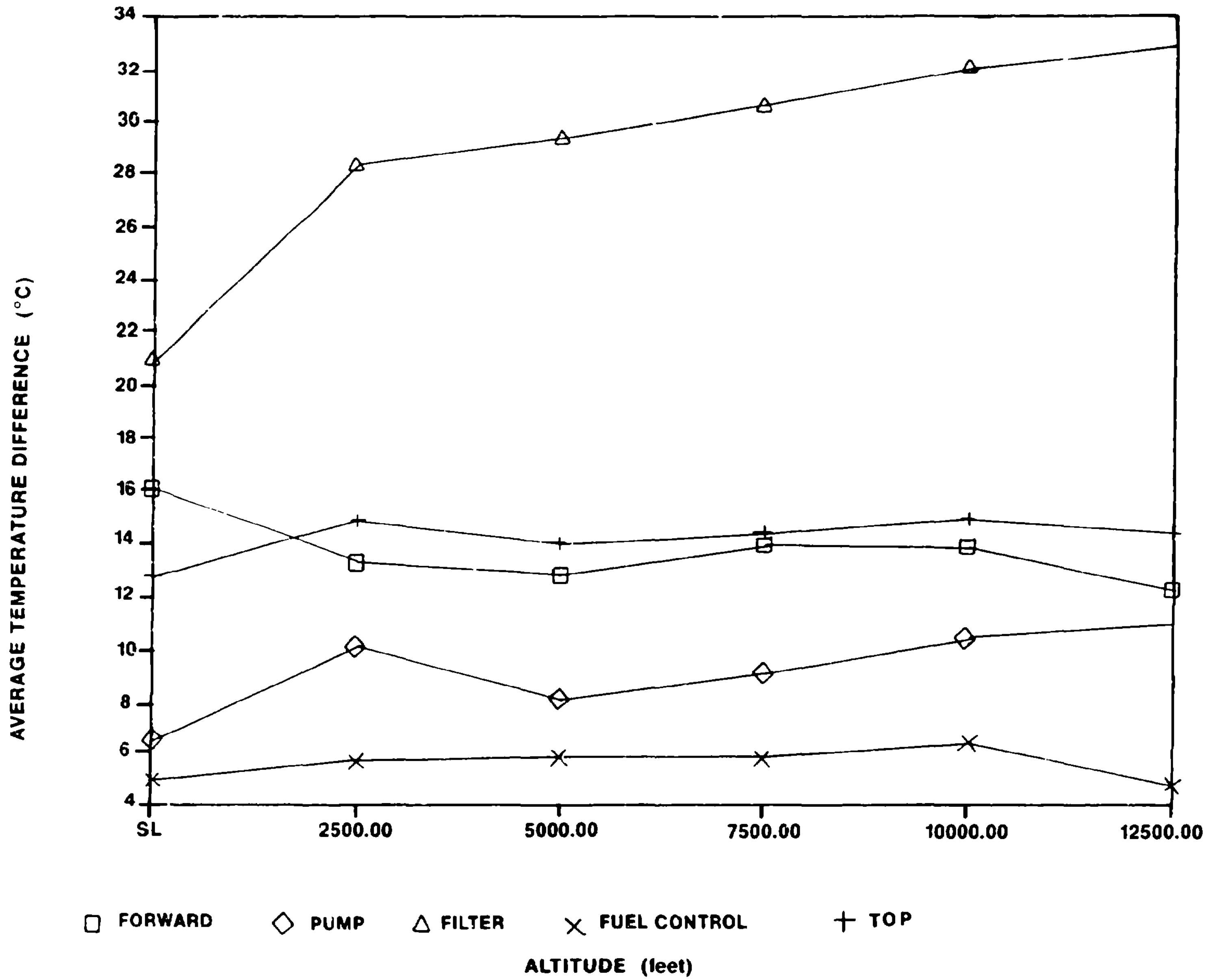


FIGURE 13. TEMPERATURE DIFFERENCE AS A FUNCTION OF ALTITUDE

CONCLUSIONS

The hot fuel behavior of a Jet-A/ethanol blend will result in more vapor formation than straight Jet-A. The conditions which are most likely to result in vapor formation are an ethanol concentration of 12.5 percent, calculated on a weight/weight basis, and a tank fuel temperature of 52 °C (125 °F). The addition of ethanol to JP-4 results in more vapor formation than straight JP-4. As with the Jet-A/ethanol blend, the conditions most likely to result in vapor formation are a concentration of 12.5 percent and a tank fuel temperature of 52 °C (125 °F). In general, the acceleration from ground idle to takeoff resulted in fuel starvation due to vapor formation sooner than any other operating mode.

The use of Jet-A/ethanol blends affected the operation of the fuel control unit on the T-63 used in the test program. The problems noted with the fuel control unit were worse following tests conducted with hot Jet-A/ethanol blends. Typical problems included hung starts, unexpected power changes, and poor repeatability (i.e., the power would not be the same for the same gas generator lever position).

Phase separation is a potential problem associated with the use of either a Jet-A/ethanol blend or a JP-4/ethanol blend (reference 1); and the use of a dual fuel system is one method used to address this problem. The use of a dual fuel system also reduced the vapor formation problems noted above, but it did not eliminate them. The worse case continued to be a fuel temperature of 52 °C (125 °F) and accelerations from ground idle to takeoff power.

The dual fuel system allowed for shutdown and startup on straight Jet-A. This appeared to reduce the severity of the material compatibility problem noted with the Jet-A/ethanol blends.

Various temperature combinations were evaluated while using ethanol and Jet-A in the dual fuel system. Fuel temperatures as low as minus 14 °C (7 °F) did not result in phase separation or operational abnormalities.

The use of methanol in the dual fuel system resulted in unstable fuel flow indications at room temperatures. The use of tertiary-butyl alcohol (TBA) as a co-solvent eliminated this problem.

Hot fuel tests were conducted with methanol and Jet-A in the dual fuel system configuration. The use of methanol resulted in vapor formation sooner than the use of ethanol under the same circumstances. A tank temperature of 52 °C (125 °F) resulted in the greatest number of problems. At this temperature, vapor formation prevented establishing steady state conditions so transient operations could not be evaluated. The duration of the methanol tests was too short to evaluate the potential for material compatibility problems.

For a given turbine outlet temperature (TOT), the power developed when using an alcohol blend was lower than the power developed when using Jet-A. Also, the corrected fuel flow is lower when using an alcohol blend than when operating on Jet-A. These two factors indicate the combustion pattern is different with the alcohol blends than with straight Jet-A. A similar pattern was noted with the use of the dual fuel system.

The break specific fuel consumption (BSFC) reflects the lower energy content of the Jet-A/alcohol blends.

Neat ethanol would not operate in the test engine. The large difference in energy content prevented the fuel controller from establishing stable steady state conditions.

The temperature profiles flown in the T-34 indicated the highest operating temperatures would occur during touch-and-go operations, immediately following a hot soak.

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APPENDIX A

DETAILED PERFORMANCE DATA

The following figures compare the performance of the various Jet-A/ethanol blends against the performance of Jet-A. The data are presented for ethanol concentrations of 5, 10, 12.5, 15, and 20 percent on weight/weight basis. In general the corrected power and fuel consumption are reduced for a given turbine outlet temperature, when operating on a Jet-A ethanol blend. The corrected brake specific fuel consumption shows that the use of Jet-A/ethanol blends adversely affects the efficiency of the T-63, though there is no apparent concentration effect. The uncorrected brake specific fuel consumption reflects the reduced operating efficiency noted above and the reduced energy content of the Jet-A/ethanol blends.

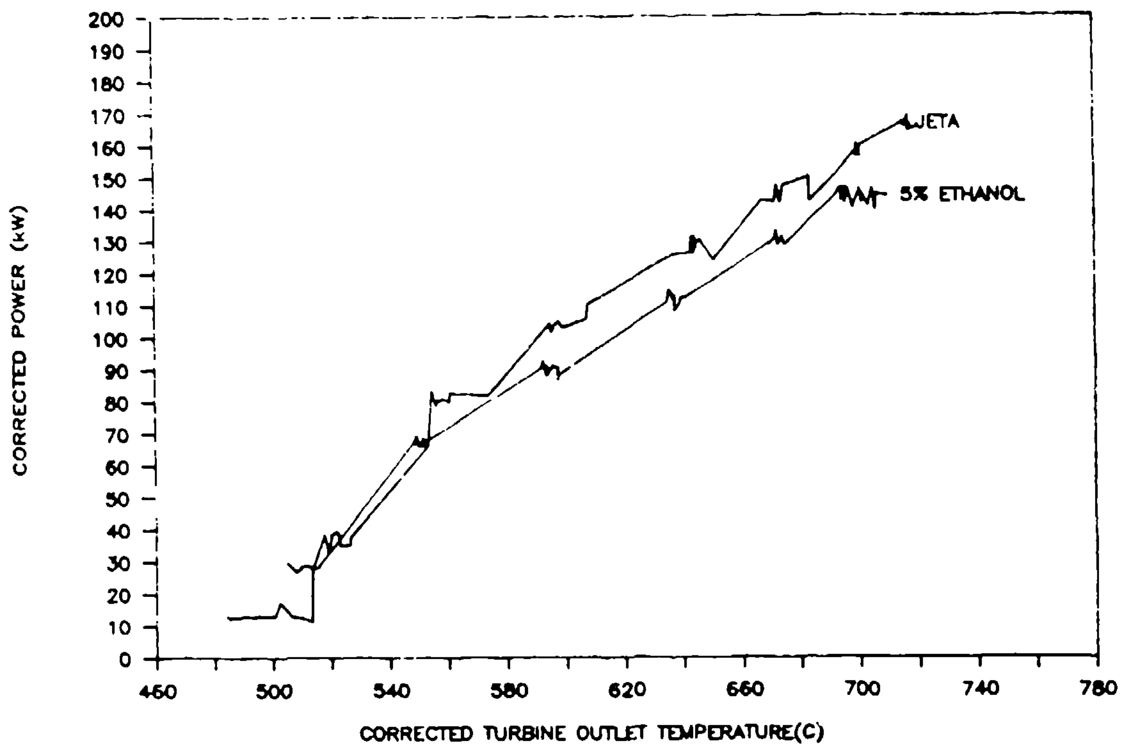

FIGURE A-1. CORRECTED POWER VERSUS CORRECTED TURBINE OUTLET TEMPERATURE

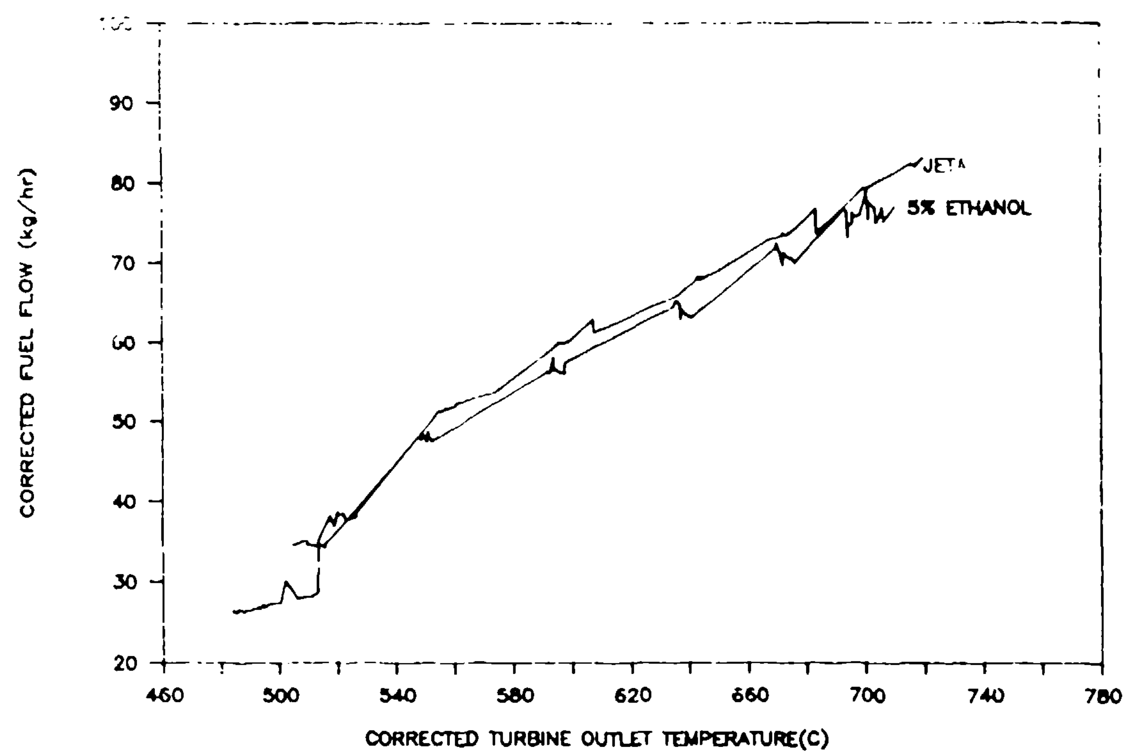

FIGURE A-2. CORRECTED FUEL FLOW VERSUS CORRECTED TURBINE OUTLET TEMPERATURE

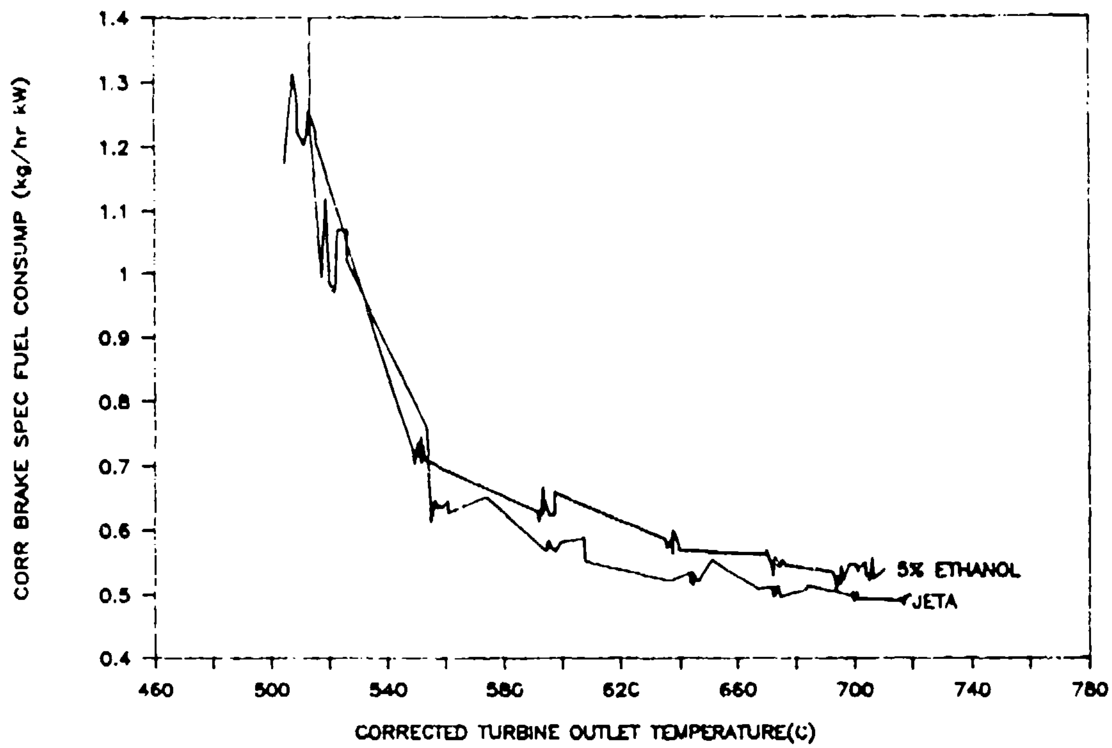

FIGURE A-3. CORRECTED BRAKE SPECIFIC FUEL CONSUMPTION VERSUS CORRECTED TURBINE OUTLET TEMPERATURE

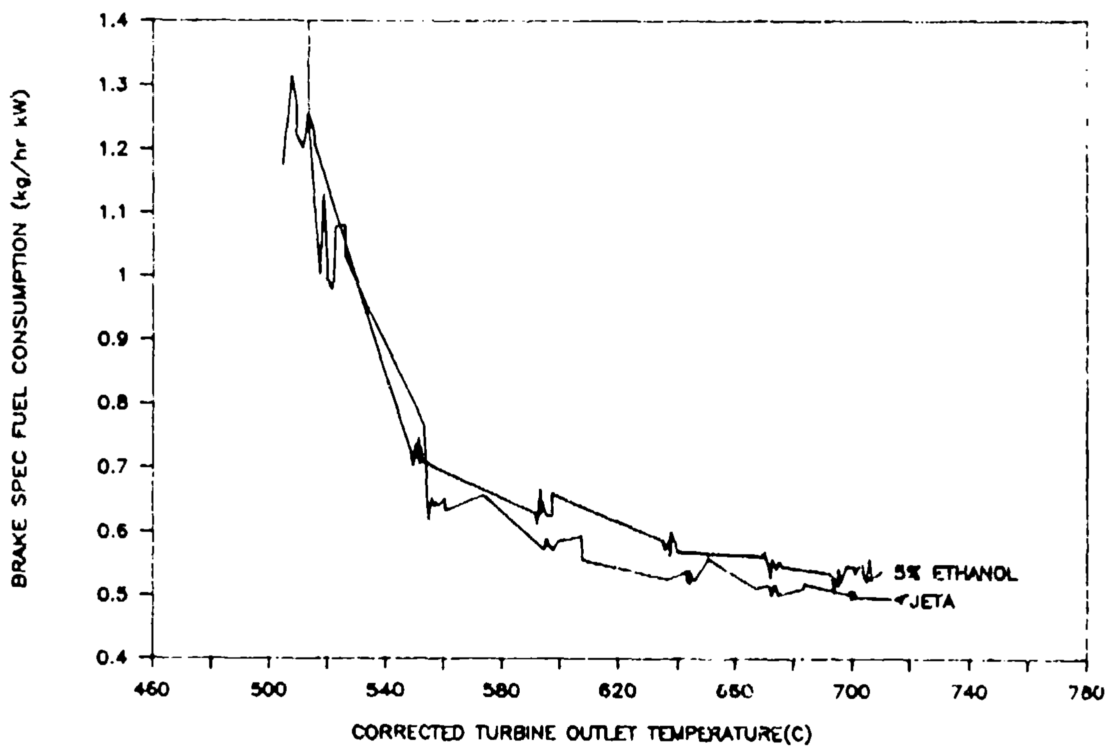

FIGURE A-4. BRAKE SPECIFIC FUEL CONSUMPTION VERSUS CORRECTED TURBINE OUTLET TEMPERATURE

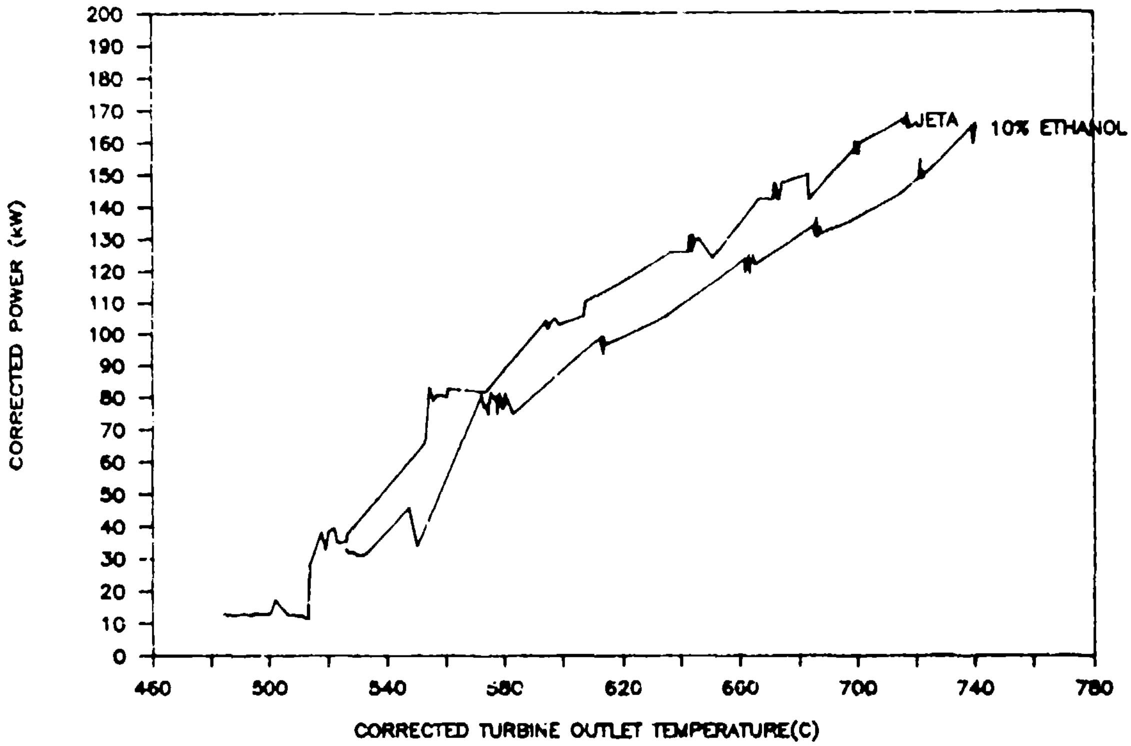

FIGURE A-5. CORRECTED POWER VERSUS CORRECTED TURBINE OUTLET TEMPERATURE

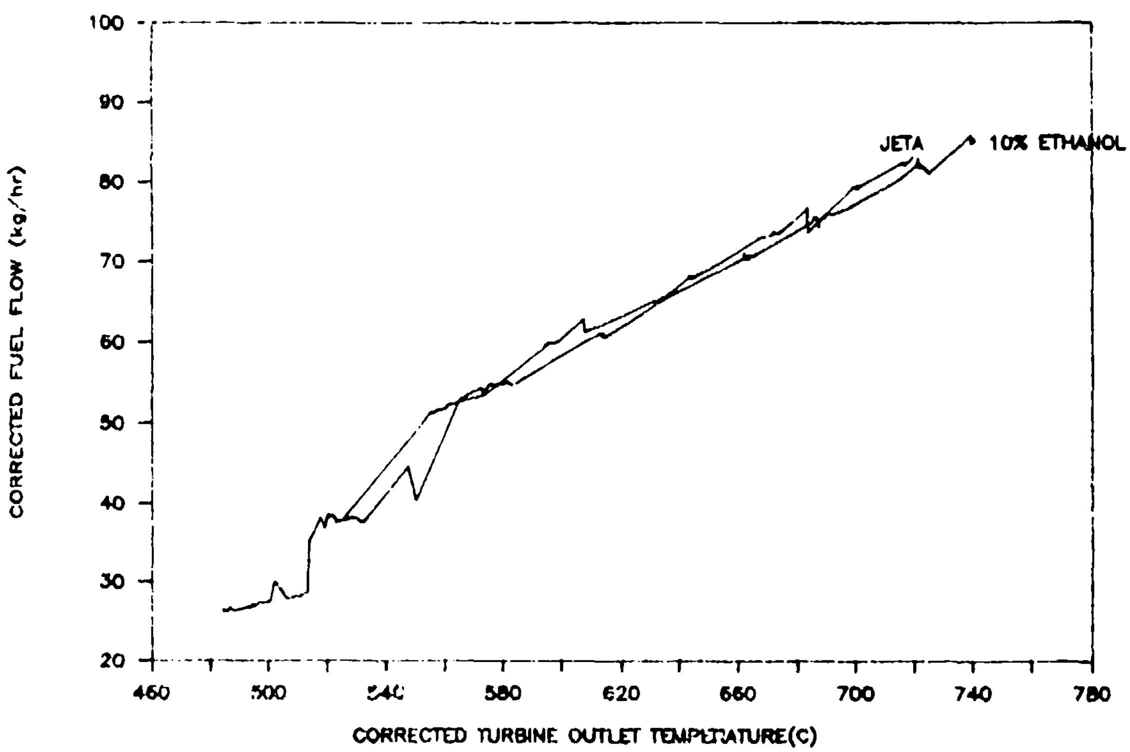

FIGURE A-6. CORRECTED FUEL FLOW VERSUS CORRECTED TURBINE OUTLET TEMPERATURE

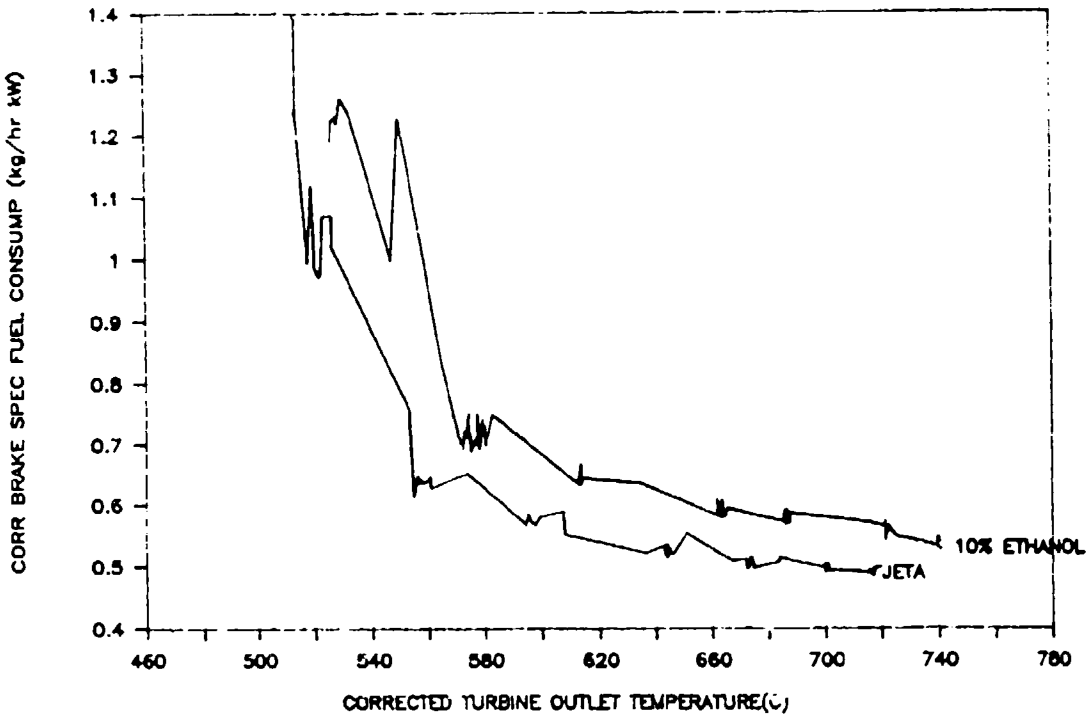

FIGURE A-7. CORRECTED BRAKE SPECIFIC FUEL CONSUMPTION VERSUS CORRECTED TURBINE OUTLET TEMPERATURE

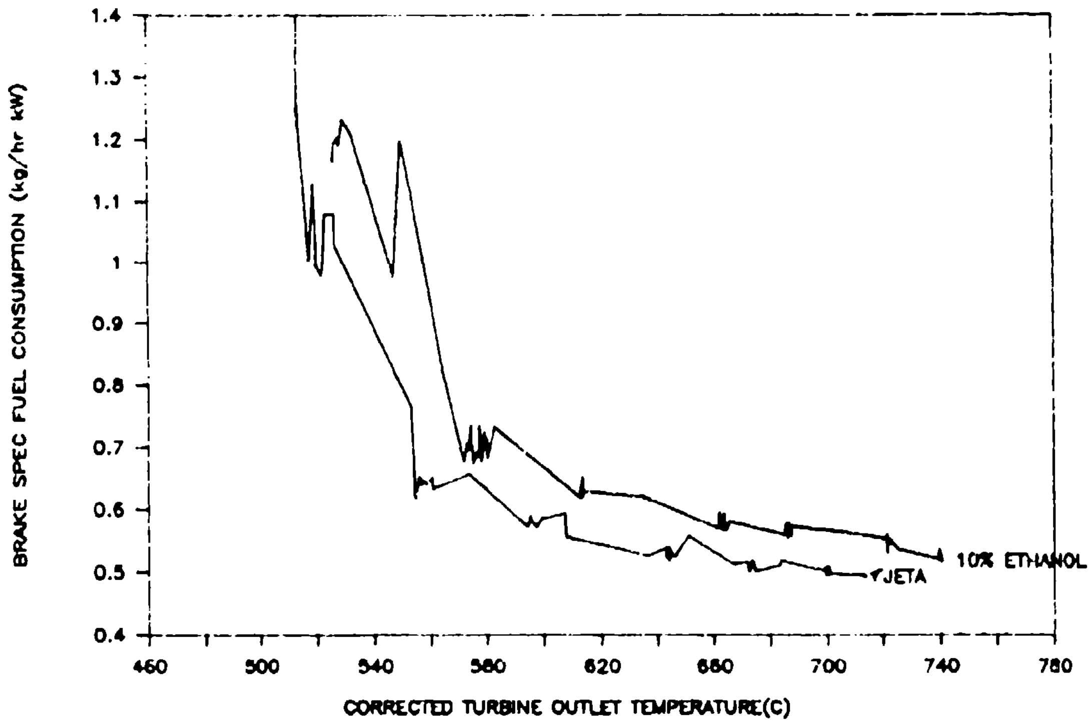

FIGURE A-8. BRAKE SPECIFIC FUEL CONSUMPTION VERSUS CORRECTED TURBINE OUTLET TEMPERATURE

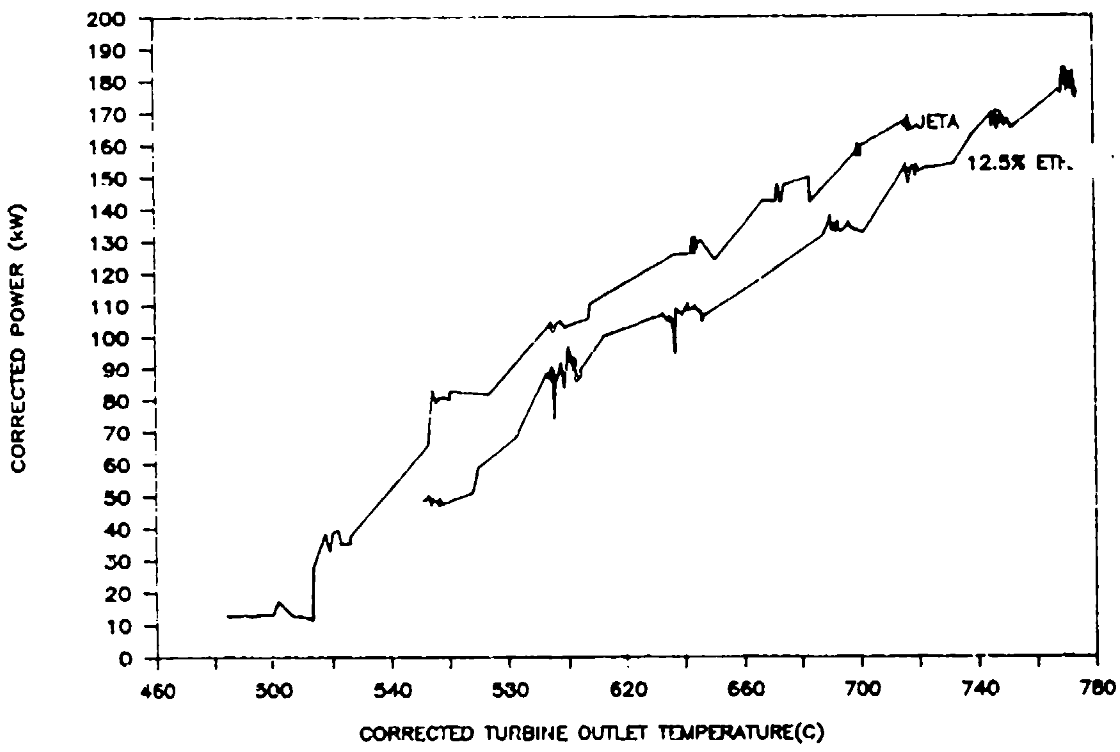

FIGURE A-9. CORRECTED POWER VERSUS CORRECTED TURBINE OUTLET TEMPERATURE

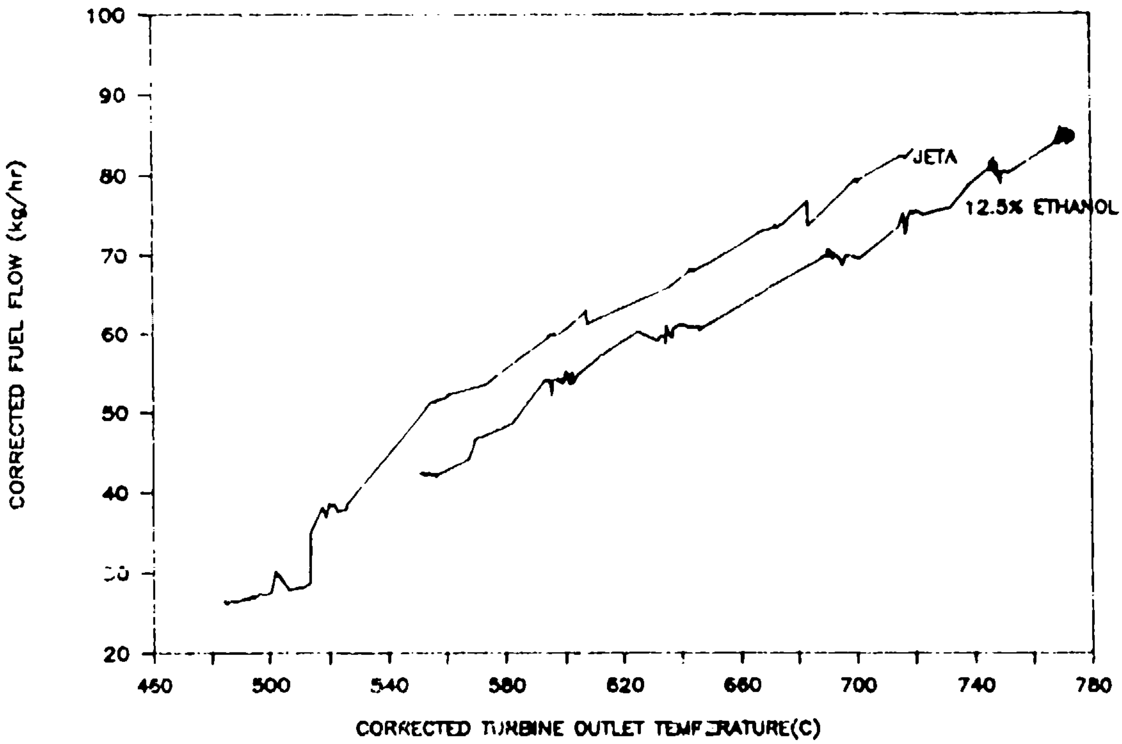

FIGURE A-10. CORRECTED FUEL FLOW VERSUS CORRECTED TURBINE OUTLET TEMPERATURE

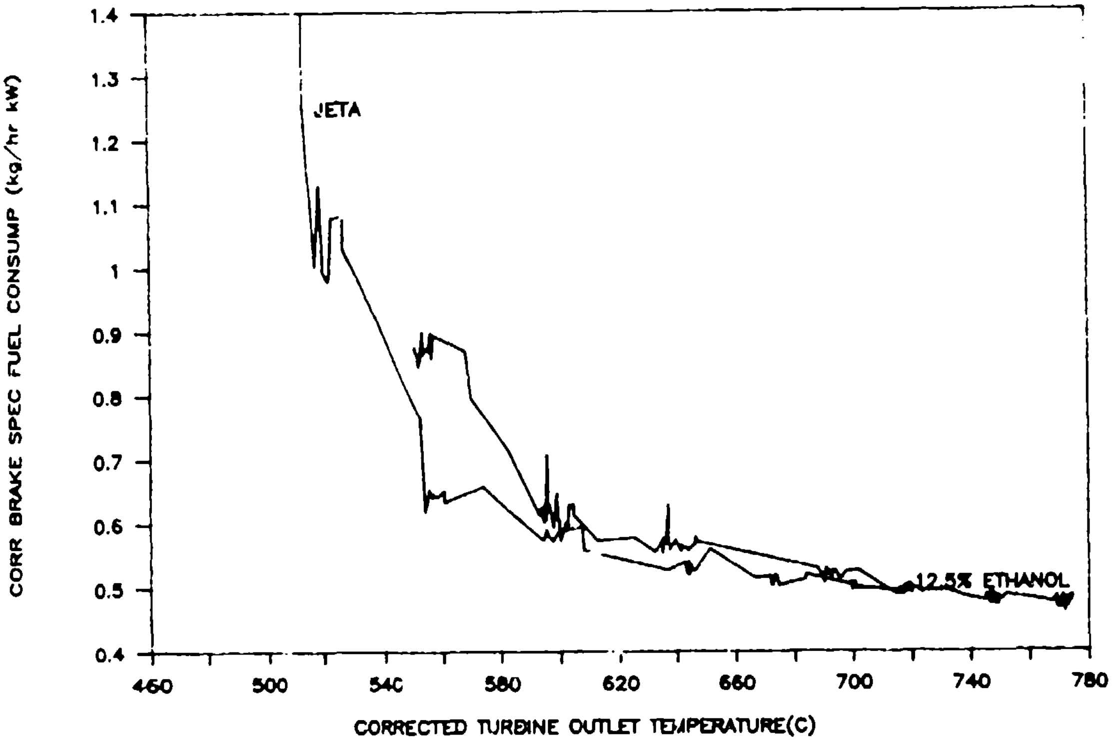

FIGURE A-11. CORRECTED BRAKE SPECIFIC FUEL CONSUMPTION VERSUS CORRECTED TURBINE OUTLET TEMPERATURE

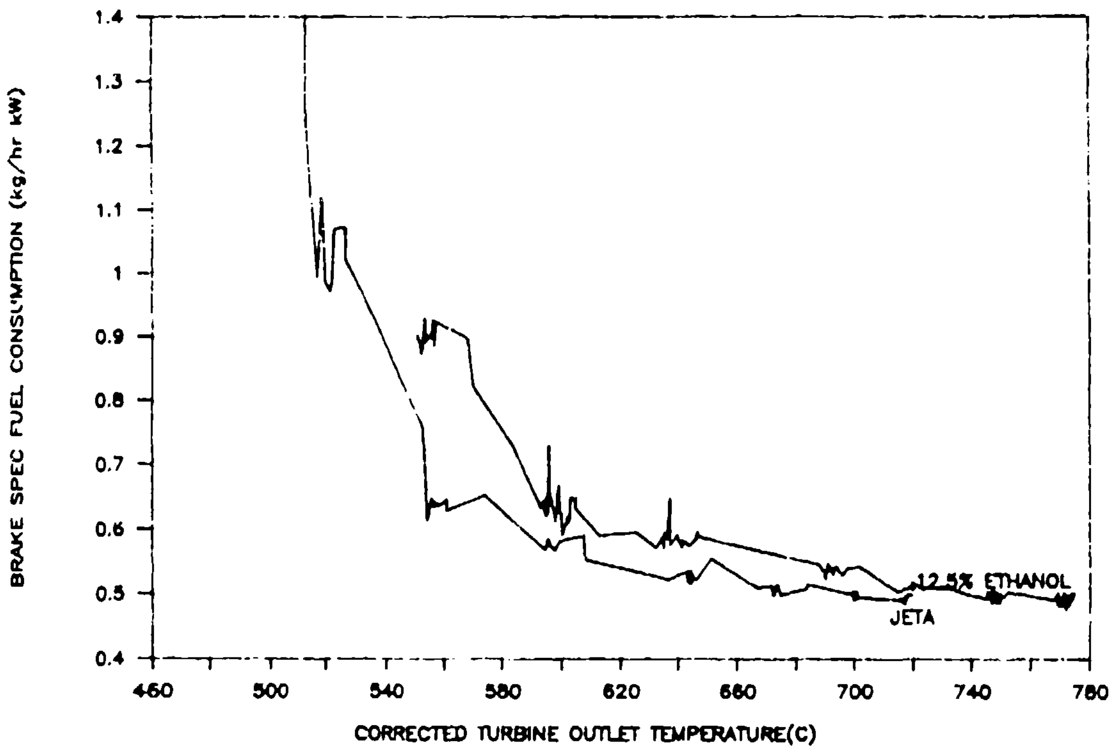

FIGURE A-12. BRAKE SPECIFIC FUEL CONSUMPTION VERSUS CORRECTED TURBINE OUTLET TEMPERATURE

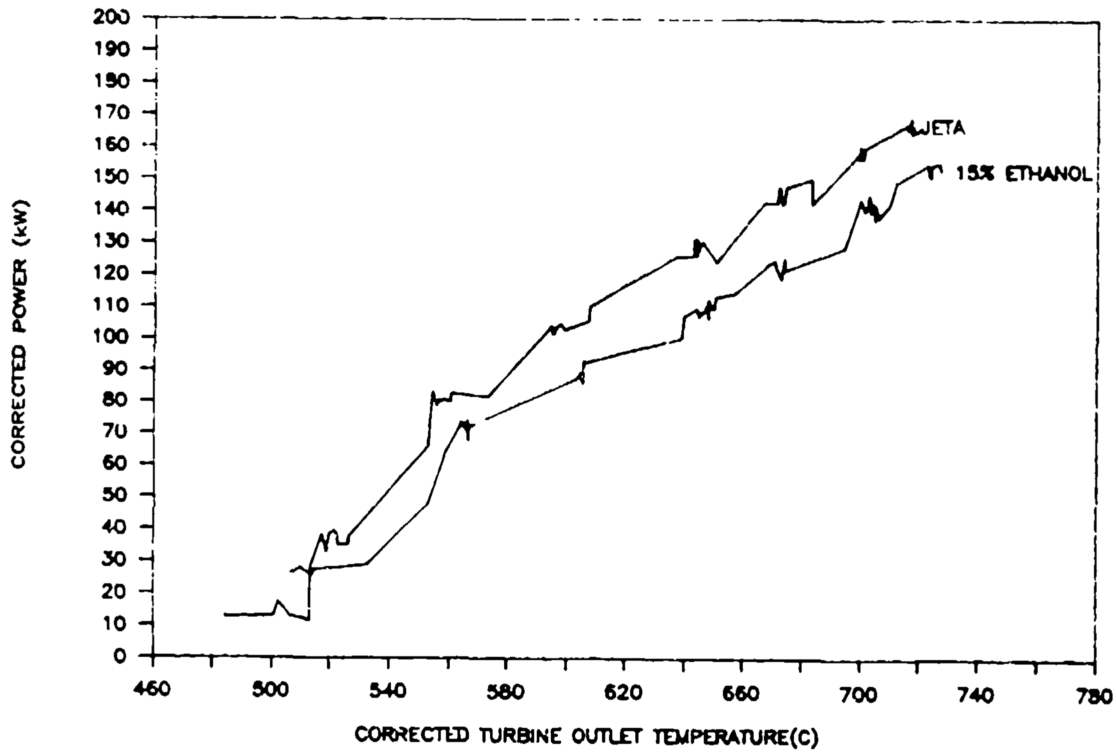

FIGURE A-13. CORRECTED POWER VERSUS CORRECTED TURBINE OUTLET TEMPERATURE

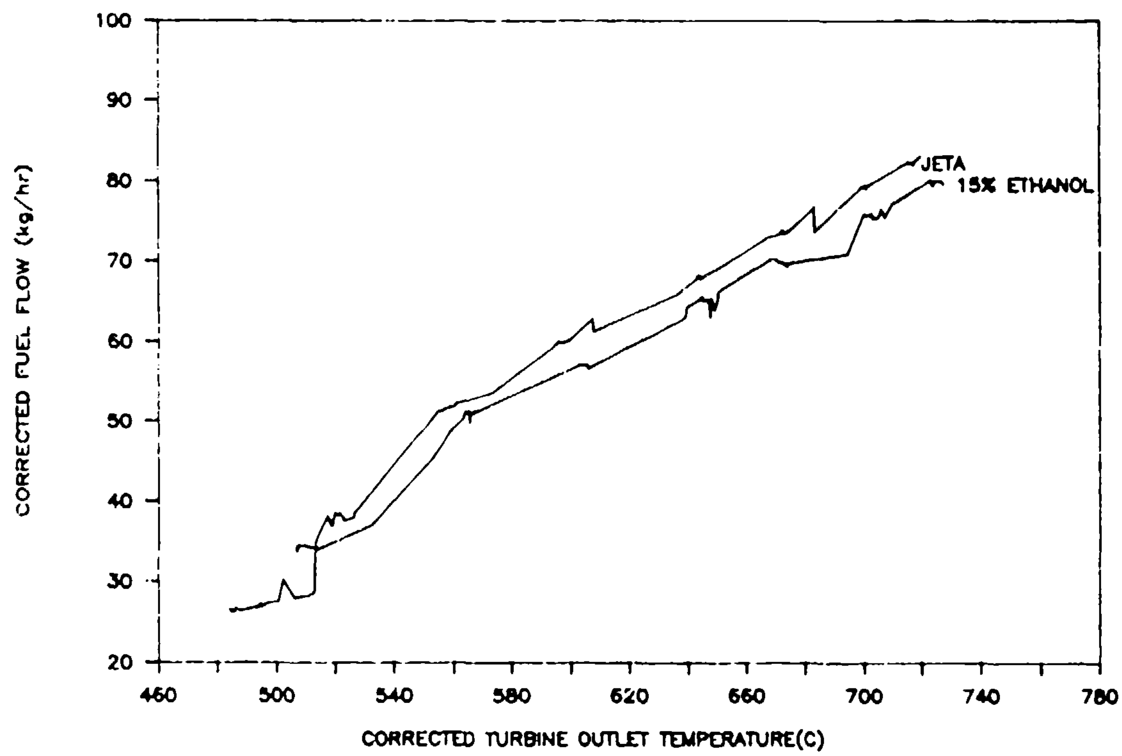

FIGURE A-14. CORRECTED FUEL FLOW VERSUS CORRECTED TURBINE OUTLET TEMPERATURE

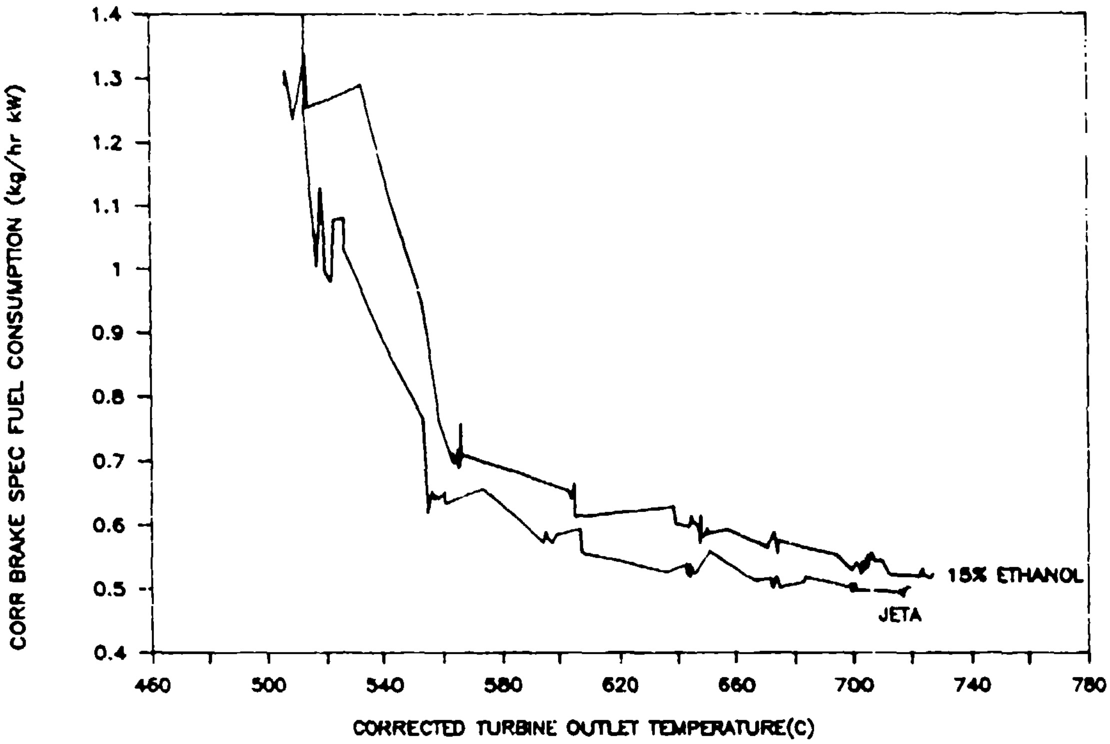

FIGURE A-15. CORRECTED BRAKE SPECIFIC FUEL CONSUMPTION VERSUS CORRECTED TURBINE OUTLET TEMPERATURE

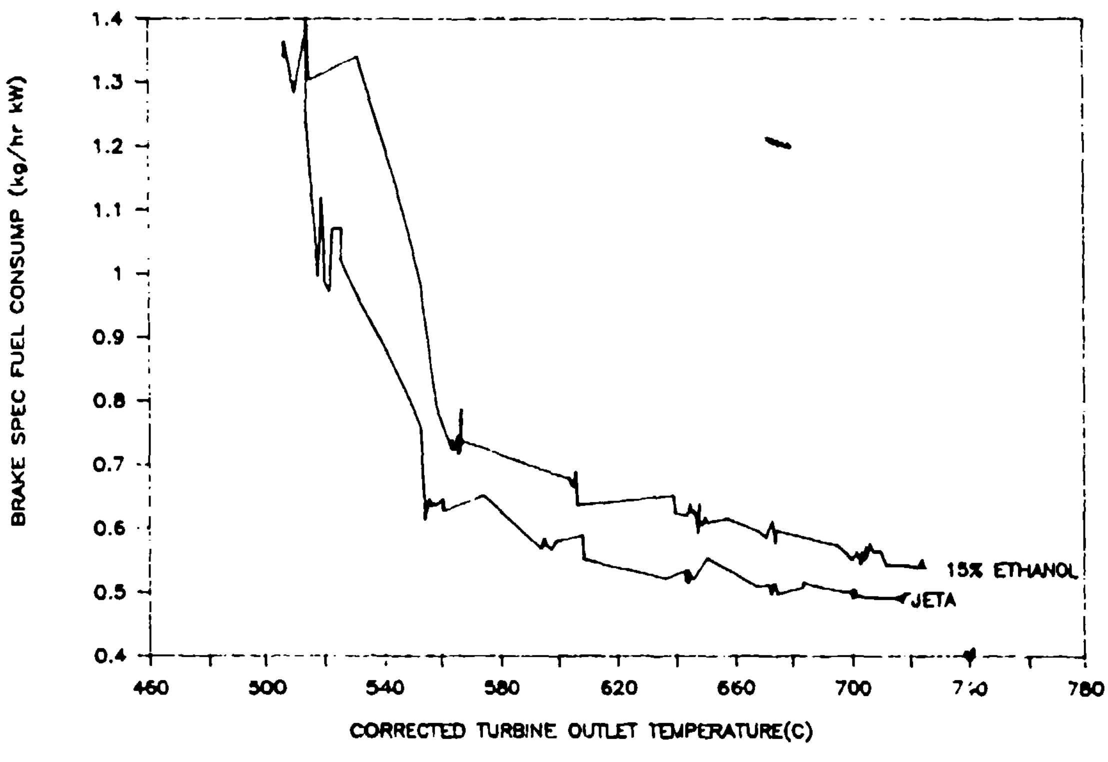

FIGURE A-16. BRAKE SPECIFIC FUEL CONSUMPTION VERSUS CORRECTED TURBINE OUTLET TEMPERATURE

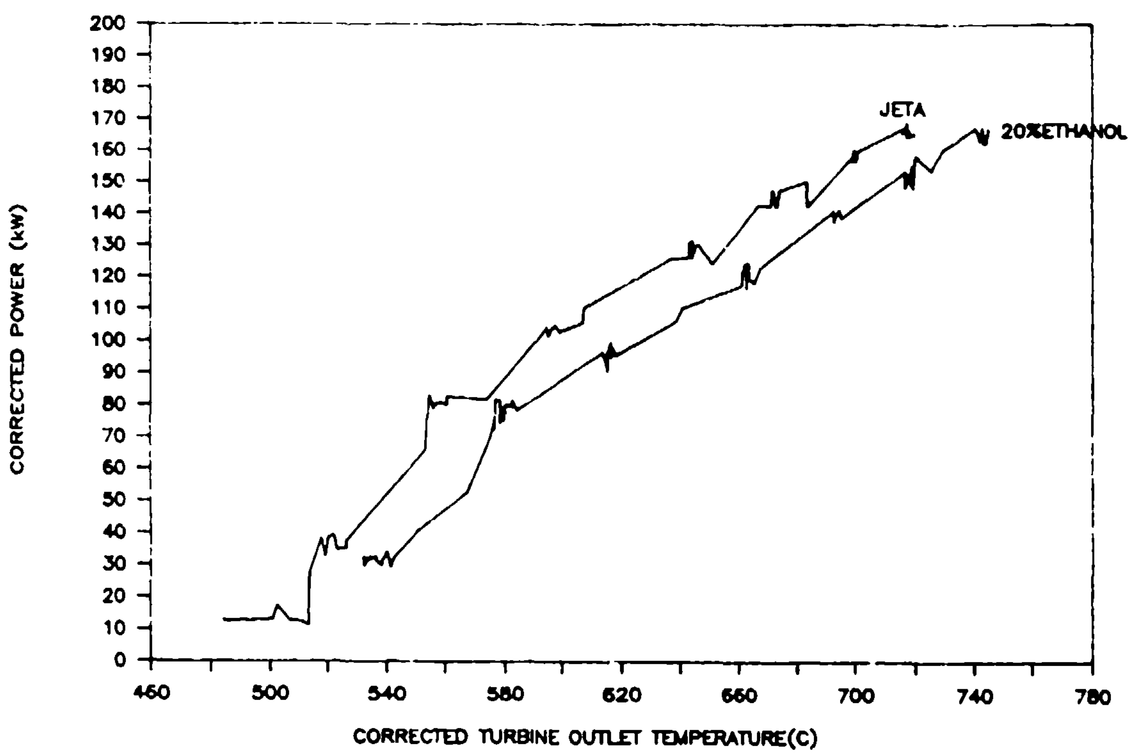

FIGURE A-17. CORRECTED POWER VERSUS CORRECTED TURBINE OUTLET TEMPERATURE

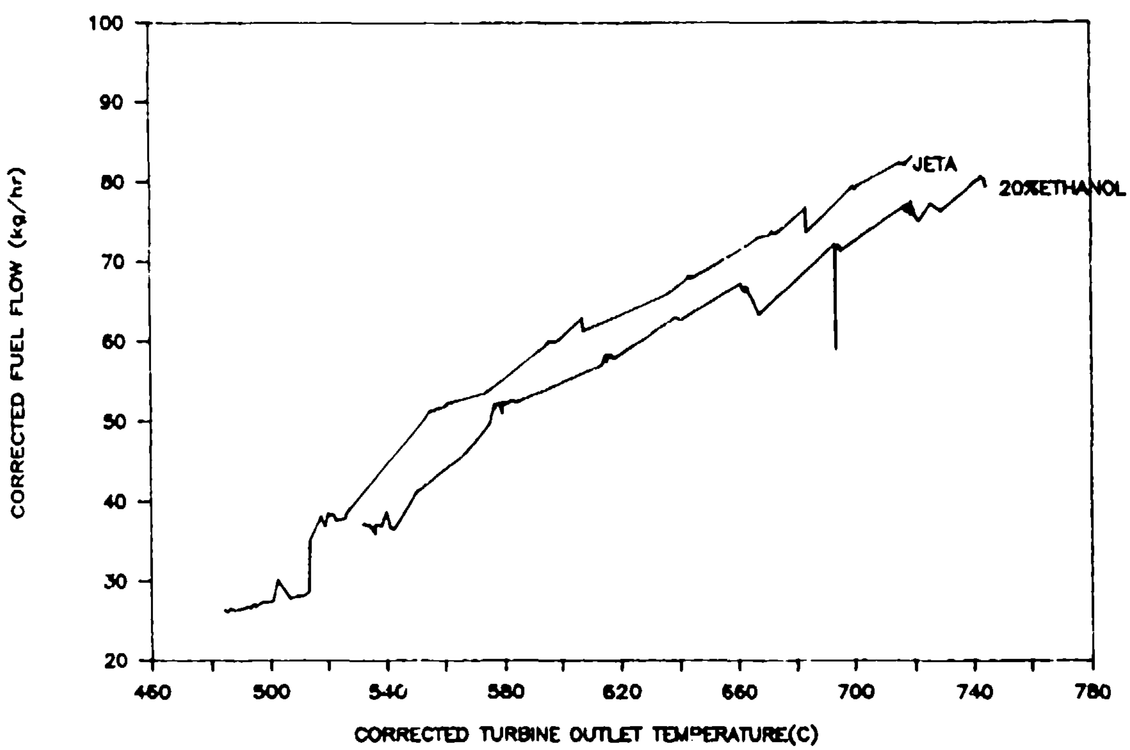

FIGURE A-18. CORRECTED FUEL FLOW VERSUS CORRECTED TURBINE OUTLET TEMPERATURE

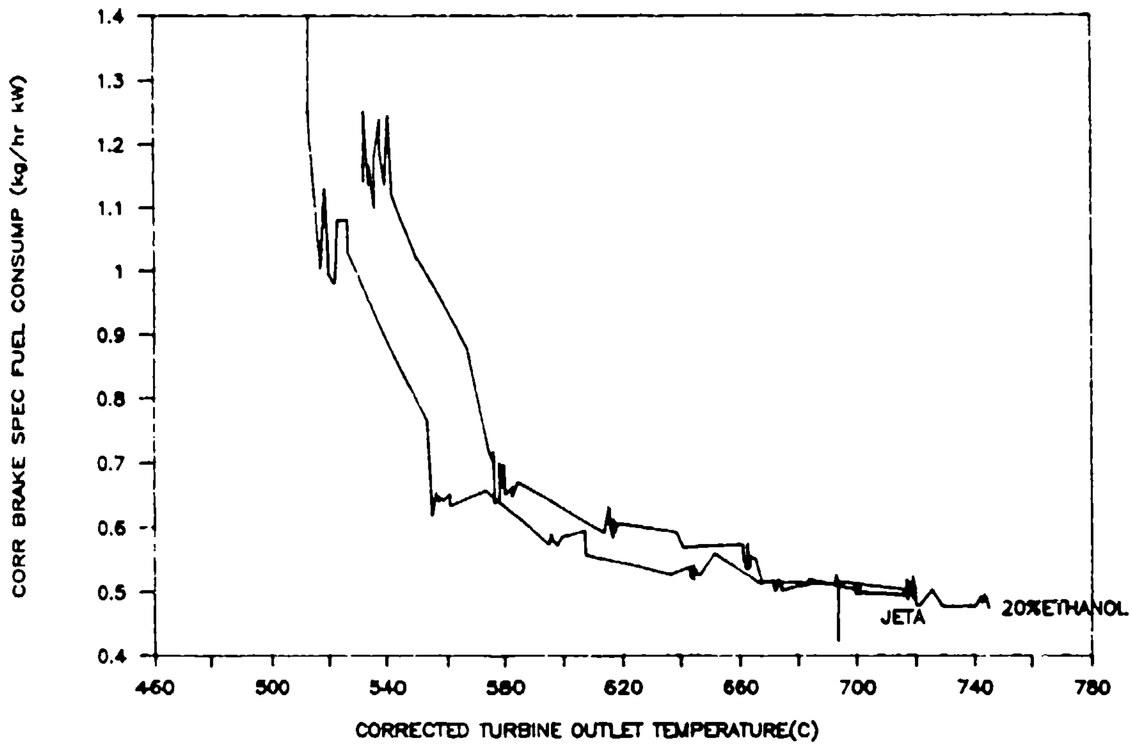

FIGURE A-19. CORRECTED BRAKE SPECIFIC FUEL CONSUMPTION VERSUS CORRECTED TURBINE OUTLET TEMPERATURE

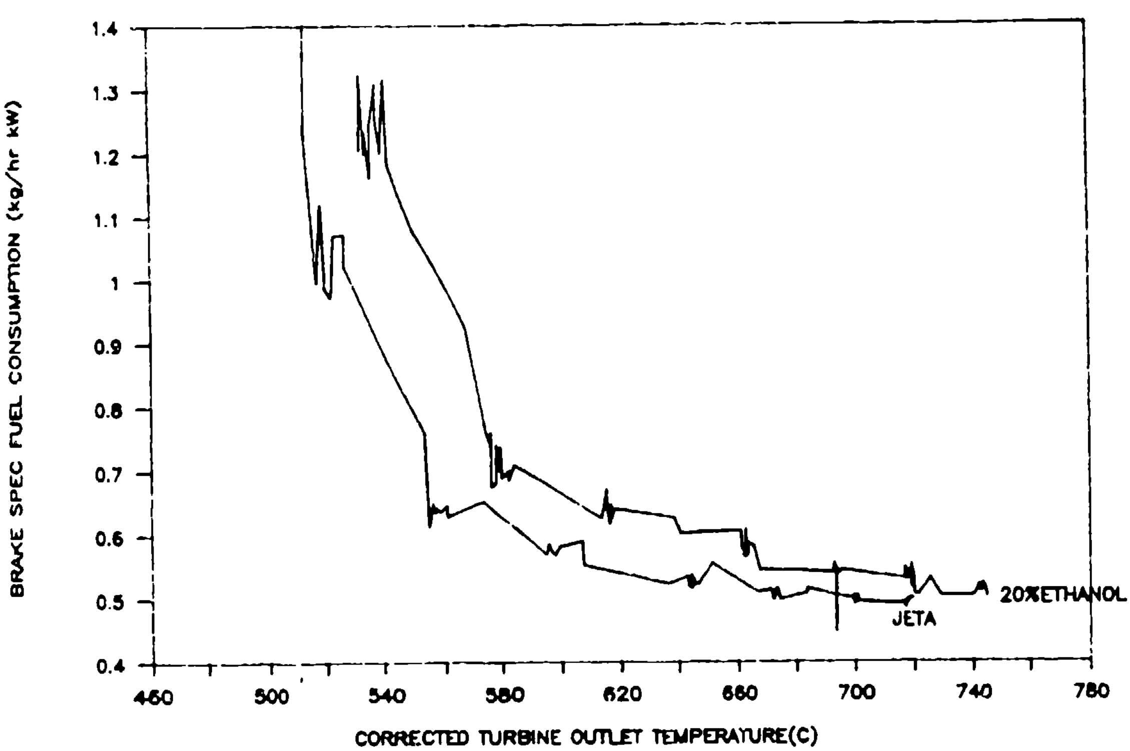

FIGURE A-20. BRAKE SPECIFIC FUEL CONSUMPTION VERSUS CORRECTED TURBINE OUTLET TEMPERATURE